The Development of the Sciences

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THE DEVELOPMENT OF THE SCIENCES

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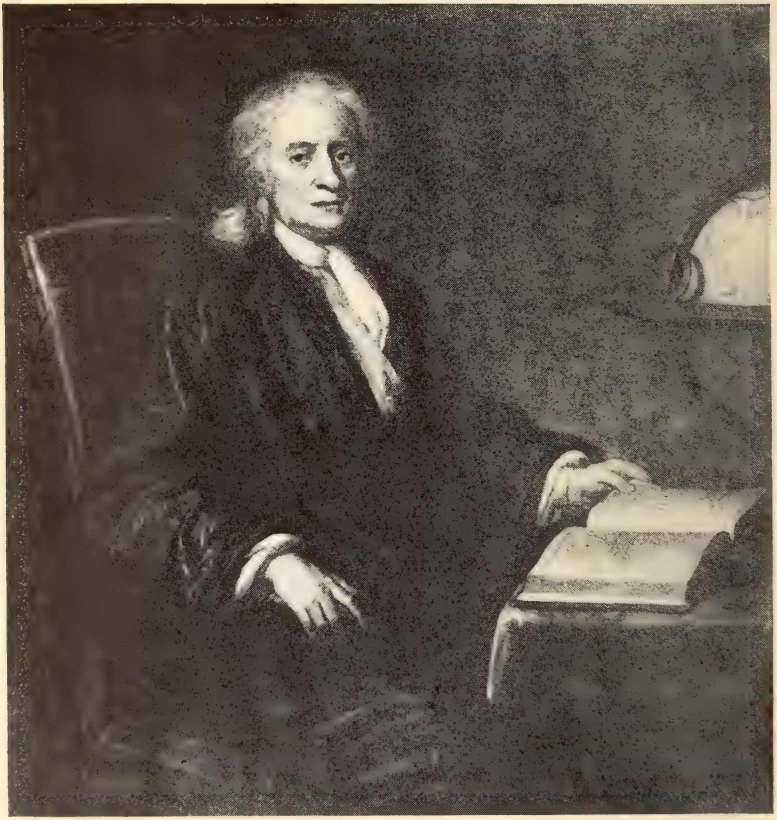

SIR ISAAC NEWTON

THE DEVELOPMENT OF THE SCIENCES

BY

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The present volume is the second work published by the Yale University Press on the Amasa Stone Mather Memorial Publication Fund. This Foundation was established August 25, 1922, by a gift to Yale University from Samuel Mather, Esq., of Cleveland, Ohio, in pursuance of a pledge made in June, 1922, on the fifteenth anniversary of the graduation of his son, Amasa Stone Mather. He was born in Cleveland on August 20, 1884, and was graduated from Yale College in the Class of 1907. Subsequently, after travelling abroad, he returned to Cleveland, where he soon won a recognized position in the business life of the city and where he actively interested himself also in the work of many organizations devoted to the betterment of the community and to the welfare of the nation. His death from pneumonia on February 9, 1920, was undoubtedly hastened by his characteristic unwillingness ever to spare himself, even when ill, in the discharge of his duties or in his efforts to protect and further the interests committed to his care by his association.

PREFACE

THE Yale Chapter of the Gamma Alpha Graduate Scientific Fraternity invited representatives of the various sciences at Yale University to cooperate in inaugurating a series of public lectures on the history of science, with the result that the following course was presented in 1920:

THE HISTORY OF THE SCIENCES

Mathematics, *Professor Ernest William Brown.*
Physics, *Professor Henry Andrews Bumstead.*
Chemistry, *Professor John Johnston.*
Astronomy, *Professor Frank Schlesinger.*
Geology, *Professor Herbert Ernest Gregory.*
Biology, *Professor Lorande Loss Woodruff.*

It fell to the lot of the representative of Biology to act as editor of the present volume, which comprises the text of the lectures, together with appendices, biographical, bibliographical, etc.

To the many individuals and publishers who generously contributed portraits of representative scientists for illustrations, the thanks of the Fraternity is cordially extended.

The Editor desires to acknowledge the continued cooperation of those members of the Fraternity who initiated the lectures, especially Mr. Walter B. Lang, now of the United States Geological Survey, and Professors William L. Crum, Chester R. Longwell, and Everett O. Waters.

L. L. WOODRUFF.

Yale University,
December, 1922.

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CHAPTER I

MATHEMATICS

By ERNEST WILLIAM BROWN

PROFESSOR OF MATHEMATICS, YALE UNIVERSITY

THE earliest dawn of science is without doubt not different from that of intelligence. But the civilized man of today, far removed as he is from the lowest of existing human races, is probably as far again from the being whom one would not differentiate from the animals if mental powers are taken as the criterion. What this difference is, neither ethnologist nor psychologist can yet tell. Perhaps the nearest approach to a definition, at least from the point of view of this article, is contained in the distinction between unconscious and conscious observation. We are familiar with both sides even in ourselves: records can be impressed on the brain and remain there apparently dormant until some stimulus brings them to fruition, and again, record and stimulus can appear together so that a train of thought is immediately started.

The faculty of conscious observation is a fundamental requirement of a scientific training, and no development can take place until it has been acquired to some extent. Although this is only the first step, it was probably a long one in the history of the race, just as it is relatively long in the lives of the majority of individuals. Reasoning concerning the observation follows, but not much success can be attained until a considerable number of observations have been accumulated. We may indeed put two and two together to make four, but experience shows that with phenomena the answer is more often

wrong than right: we need much more information in order to get a correct result.

We expect, then, that the earlier stage of a science will be one not so much of discovery as of conscious observation of phenomena which are apparent as soon as attention is called to them. The habit once acquired, the search for the less obvious facts of nature begins, and in the search many unexpected secrets are found. Once a body of facts has been accumulated, correlation follows. The attempt is made to find something common to them all and it is at this stage that science, in the modern sense, may perhaps be said to have its birth. But this is only a beginning. The mind that can grasp correlation can soon proceed to go further and try to find a formula which will not only be a common property, but which will completely embrace the facts; that is, in modern parlance, a law which groups all the phenomena under one head.

The formula or law once discovered, consequences other than those known are sought, and the process of scientific discovery begins. Realms which could never have been opened up by observation alone are revealed to the mind which has the ability to predict results as consequences of the law, and thence is found the means by which the truth of the law is tested. If the further consequences are shown to be in agreement with what may be observed, the evidence is favorable. If the contrary, the law must be abandoned or changed so as to embrace the newly discovered phenomena. The process of trial and error, or of hypothesis and test, is a recurring one which embraces a large proportion of the scientific work of today.

Scientific development has two main aspects. One is the framing of laws in order to discover new phenomena and develop the subject forward so as to open out new roads into the vast forest of the secrets of nature. The other is the turning backward in order to discover the foundations on which the

science rests. Just as no teacher would think it wise to start the young pupil in chemistry or physics by introducing him at the outset to the fundamental unit of matter or energy as it is known at the time, but will rather start in the middle of the subject with facts which are within the comprehension of his mind and the experience of his observation, so science itself has been and must necessarily be developed in the same manner. We proceed down to the foundations as well as up to the phenomena.

This twofold aspect of scientific research has had revolutionary results in the experience of the last half-century. It has fundamentally changed the ideas of those who study the so-called laboratory subjects in which observation with artificially constructed materials goes hand in hand with the framing of laws and hypotheses, but it has changed the study of mathematics in an even more fundamental manner. In the past, geometry and arithmetic were suggested by observation and practical needs and the development of both with symbolic representation proceeded on lines which were dictated by the problems which arose. The methods of discovery in working forward were not essentially different from those of an observational science, except perhaps that the testing of a new law was unnecessary on account of the rules of reasoning which accompanied them and became embodied into a system of logic. It was, however, in proceeding backward to discover the foundations that the whole aspect of the subject changed. While many of the hypotheses were suggested by observation and were known by numerous tests to be applicable to the discussion of natural phenomena, it became evident that the actual hypotheses used were independent of the phenomena. The laws which are at the basis of geometrical reasoning are not necessarily natural laws: they can equally well be regarded as mere productions of the brain in the same sense as we might imagine a race of intelligent beings on another planet free

from some of our limitations or restricted by limitations from which we are free. It is seen to be the same with the rules of symbolic reasoning which have gradually grown up. A geometry without Euclid's axiom of parallels has been constructed perfectly consistent in all its parts. This is built up of a set of axioms which constitute its foundation together with a code of reasoning by which we develop the consequences of the axioms. The same is true of geometries which involve space in more than three dimensions. It is somewhat easier to imagine symbolic developments which have their foundations different from those of our school and college algebras because there is no obvious connection between these rules and the phenomena of nature.

It may be asked what limitation is there in the development of mathematical theories if any set of axioms may be laid down. Theoretically there is none, except that if we retain our code of reasoning about them such axioms must not be inconsistent with one another. A certain sense of the fitness of things restrains mathematicians from a wild overturning of the law and order which have been established in the development of mathematics, just as it restrains democracies from trying experiments in government which overturn too much the existing order of affairs. Changes proceed in mathematics just as in politics by evolution rather than by revolution. The slowly built up structure of the past is not to be lightly overturned for the sake of novelty.

The developments traced above apply mainly to the subject of mathematics apart from its applications to the solution of problems presented by nature. Applied mathematics is a method of reasoning through symbols by which we can discover the consequences of the assumed laws of nature. The symbolism which we adopt and the rules we lay down with which to reason are immaterial, provided they are convenient for the objects we have in view. One feature must not be for-

gotten. We can never deduce the existence of phenomena through mathematical processes which were not implicitly contained in the laws of nature expressed at the outset in symbols. One cannot take out of the mathematical mill any product which was not present in the raw material fed into it. It is the purpose of the mill to work up the raw material, and the better the machinery the more finished and more varied will be the product.

To write a connected story of mathematical development within the limits of a brief article on a consistent plan without making it a mere catalogue of names and results is a difficult, perhaps impossible, task and no attempt is made here to accomplish it. If we try to lay stress on the workers rather than on what they achieved, in one period we encounter schools which developed particular subjects, in another, outstanding figures with or without influence on contemporary development, and in still another, numerous investigators who contributed in varying degrees to the advances made in their age. On the other hand, if the development of ideas be the basis, parallel developments followed independently by different schools sometimes occur, at another time general methods of treatment seem to pervade, and again we may find some fundamental advance made, the effect of which is not felt for many years. Consequently the plan which seems to fit best any particular period has been adopted for that period. Another difficulty consists in assigning the relative values to either men or ideas, about which probably no two persons will agree. There is, however, one stumbling-block which is peculiar to mathematics. The very names themselves of important branches of pure mathematics convey no meaning to very many scientific readers who are not trained mathematicians and to whom alone this article is intended to appeal. An attempt at brief definition has sometimes been made, but it can at best only give a partial view of the subject even with concrete illustra-

tions of its significations. In the general outline, the historical development has been followed, but the methods of carrying it forward have varied with different periods. When a choice of names mentioned has to be made, a rough guide has been furnished in the earlier periods by selecting those who have taken the step forward which has rendered the subject capable of expansion or application by others as judged in the light of present knowledge. In the nineteenth and present centuries to carry out this method has proved to be beyond the ability of the writer; consequently, in most cases personal mention has only been incidental and the names of many of those who have done great service are missing. Fortunately, the history of mathematics has received much attention in articles and separate volumes and to them the reader who is interested in obtaining fuller information is referred.

The earliest traces in the form of written records have come to us from the Babylonians, mainly in the form of clay tablets which appear to have been made at least 2000 years B. C. They show a knowledge of numbers which indicates that their civilization must have been far removed from the low stages in which many native tribes exist at the present day. Simple counting with the fingers of the two hands can be considered as the first stage, but beyond ten some new system must be devised. It is doubtful whether the Babylonians had learned the method of position, that is, that the first figure to the right shall represent the units, the next figure the tens, and so on. They had constructed numbers with sixty as the base of the system instead of ten. They could write numbers exceeding a million, many tablets giving tables of squares, and they also used fractions. Their geometry, however, was only in an elementary stage. But in astronomy they seem to have passed beyond the first stage of observation and to have been able to classify the results, for they possessed a knowledge of the

Saros or period of 18⅔ years in which the eclipses of the sun and moon recur; this must have involved a long period of observation and record as well as the ability to classify the results and it may perhaps be regarded as the earliest recorded scientific deduction from observation.

Concurrently with this civilization was one of perhaps equal development in Egypt. The Ahmes Papyrus, which is dated some 1500 B. C., shows that the Egyptians had not only already constructed an arithmetic but had started the solution of what we now call equations of the first degree with one unknown. There was no general method for solving the problems and although symbols for addition, subtraction, and equality occur, these were little used. In geometry they were also somewhat in advance of the Babylonians, apparently on account of practical needs in land surveying. It is generally agreed that the pyramids show evidence of astronomical observation in their orientation with respect to the stars, and they certainly show evidence of a knowledge of geometrical form. As these monuments appear to go back some 4000 years B. C., we have evidence of considerable development much further back even than the times indicated by the Babylonian tablets or the Ahmes Papyrus.

But the first real evidence of the scientific spirit comes from Greece. While the Greeks probably inherited some of the accumulated knowledge of both Babylonia and Egypt, they transformed much of the raw material thus acquired into a finished product which has survived to our own times. Much the most remarkable of all that we inherit from them in science, is the change which they effected in the study of geometry. The love and knowledge of form which is so strikingly exhibited in their buildings and statuary was also applied to geometrical figures. Development of logic and a real desire to know the sources of all things, was applied to the same study. Thus Greek geometry was not only a consideration of

the properties of straight lines and circles, but much more, a development of those properties by processes of thought from axioms laid down as a basis. If the modern mathematician can see defects of logic in much that has been handed down, he still follows Greece in the method of thought by which he deduces one result from another. Those same methods, indeed, are used to criticize the defects of the early work and that he is able to do so is chiefly due to the extended range of ideas which the developments of all forms of science have been able to give him. Some of the great names of antiquity in what we now term the humanities, are also great names in the history of science: Plato and Aristotle played no small part in the early developments.

The Greek school appears to have started about the seventh century before Christ, and it lasted nearly a thousand years, coming to an end finally after a long struggle against the stifling effect of the Roman conquest. For the first three hundred years Greece, a free nation, or at least under the government of its own citizens, found leisure to devote to intellectual pursuits, as a host of great names testifies. The war against Asiatic invaders in the fifth century B. C. seems to have quickened rather than retarded the development of literature, science, and the arts, perhaps under the spur of the construction of a single nation with democratic ideals from numerous small states. The conquest of Greece by Alexander in 330 B. C. transferred the scepter nominally to Egypt through the enlightened policy of the Ptolemys who founded and encouraged schools of learning in Alexandria. But those who taught and worked there were all under Greek inspiration, and most of the advances were made by those of Greek origin. Apparently the foreign soil and alien patronage, however, gave only a temporary lease of life, for a decline started soon after and was accentuated in the first century B. C. when the Romans conquered Egypt and gained command of the whole civilized

Gottfried Wilhelm Leibnitz.

John Napier.

René Descartes.

Pierre de Fermat.

world. They themselves contributed little. The fall of the Roman Empire through the incursion of the northern tribes, the rise and spread of Mohammed's followers, who, it is true, brought in translations of Greek mathematics but contributed little themselves, the repression of free thought by the higher ecclesiastical authorities, left no opportunity for schools of science to grow. But few names appear in this period and those who sought to study the problems of nature had little opportunity to extend the borders of knowledge.

A real awakening appeared towards the end of the fifteenth century. Revolts against ecclesiastical authority in England by the reigning sovereign, and later in Germany by Luther, the great geographical enterprises which soon resulted in a knowledge of the principal land areas of the earth, the curbing of royal ambitions by the defeat of the Spanish Armada, and the brief interlude of a commonwealth in England, had their counterpart in the invention of printing and the appearance of scholars advancing knowledge in almost all the civilized countries of the western world. The tremendous steps taken in the course of two centuries, culminating in Newton and Leibnitz, finally placed scientific investigation on a plane where it became largely indifferent to what was going on in the political world, and where it was able to pursue its own course, hampered, it is true, by wars and revolutions, but never without great names which will live as long as the history of scientific development is remembered.

This rapid sketch may serve to assist in seeing how the progress of scientific thought has been related to the development of civilization. We are all apt to regard our own concerns as independent developments and too often the history of science is treated in the same way. But in looking at the subject over long periods of time, we should treat scientific development as one of the phenomena which will illustrate progress or decline. The attitude of mind which leads to a

search for the secrets of nature is simply one manifestation of a common desire for progress and if so, we should see signs of this desire in many directions. The ultimate causes which underlie the changes which have taken place—which produce periods of activity and inactivity in a whole people or group of peoples—are unknown and will probably only be finally found in the laboratories of the biologist and the physicist. All we can do now is to correlate the facts as far as possible and record them for future use.

Let us return to the Greeks and examine a little more in detail their contributions. In doing so we are at once faced by the difficulty that most of our knowledge comes to us second hand and in the form of treatises which gathered together past achievements. But few names survive and it is not always easy to apportion the credit. It sometimes appears that a name represents a school rather than an individual. This is certainly true to some degree of Pythagoras, to whom is usually credited the theorem that the sum of the squares on the sides of a right-angled triangle is equal to that on the hypotenuse. He certainly formed schools, but these were conducted as secret societies, the members of which might not divulge the knowledge they attained. Their continued existence for a long period of years was probably much assisted by the custom or rule of attributing all discoveries made by the members to their founder, thus avoiding much heartburning and jealousy. Nevertheless, Pythagoras seems to have been responsible for placing geometry on a scientific basis by investigating the theorems abstractly. Briefly stated, it may be said that up to the middle of the fifth century B. C., shortly after the battle of Salamis, the Greeks had discovered the chief properties of areas in a plane and most of the regular solids. Their clumsy notation for numbers handicapped them in arithmetic, but they knew such properties as that the difference of the squares of two consecutive numbers is always an odd number, they defined

progressions of different kinds, and they had some acquaintance with irrational numbers. This was perhaps the first school which devoted itself to investigation for its own sake without any special reference to possible applications to physical problems.

Then followed the golden age of Greece with Hippocrates of Chios, Euclid, Archimedes, Apollonius, Hipparchus, and a number of others less well known. Plato and Aristotle must also be included for their contributions to the forms of logical reasoning which should be adopted, and Plato in particular contributed in this respect to an extent which has lasted until our own times. Euclid, whose personality is decidedly nebulous, wrote a textbook on the geometry of the line and circle by which most mathematicians for the next two thousand years were introduced to the subject: it is indeed only during the last few decades that it has been replaced by modern texts. Apollonius did much the same thing for the curves of the second degree—the ellipse, parabola, and hyperbola. While we know little of Euclid's own contributions as a discoverer, it is fairly certain that Apollonius had not only mastered all that was previously known, but greatly extended that knowledge himself. But of all those who lived up to the time of Isaac Newton, there can be little doubt that Archimedes is the chief. He is recognized as the founder of mechanics, theoretical and practical. His work on the lever alone entitles him to fame: "give me a fulcrum and I will move the world." He initiated the sound study of hydrostatics, advanced geometry by discovering how to find the area of a sphere and that cut off from a parabola by a straight line. He also discussed spiral curves, finding many of their properties. In arithmetic he seems to have had methods for dealing with very great numbers similar to those we now use by the index of the power of ten which can represent the number. These brief statements are only symbolic of what he achieved. His activities were very ex-

tended, and he preferred the modern custom of writing essays, or memoirs as we now call them, rather than treatises or textbooks. The tradition runs that he was killed at the fall of Syracuse to the Romans because, absorbed in a geometrical diagram, he insulted the Roman soldier who was spoiling it.

Hipparchus was mainly an astronomer, and indeed one of the founders of the art, and it was in the course of his work that he opened the way to the use of trigonometry as an aid when angles as well as lines had to be measured.

During the following centuries up to the Fall of Rome in A. D. 476, there were no great advances, the principal name of the period being that of Diophantus, whose main contribution was a study of indeterminate equations. Algebra seems to have been developing very slowly and naturally, first by abbreviation of the words of a statement, next by a typical word (heap) and later by a symbol to represent the unknown, and finally by the adoption of symbols for common operations, like those of addition, equality, and so on. Diophantus took a great step in this direction, and he may be regarded as the father of algebra in the main stream of the development of mathematics, in the sense that he placed it on a basis which rendered it capable of development. However, his work received no recognition at the time and was not revived for more than a thousand years.

We must now say something about some of the tributaries which paralleled the main Grecian stream and connected with it through the Moorish invasion of Europe during the seventh and eighth centuries. During the time of their dominance the Romans, if they contributed little, at least allowed development to continue in the centers of civilization. The Arabs, however, following the example set by the theologians, who by this time were beginning to come into power, had little use for scientific works and investigation, and between them they destroyed completely the greatest library and museum of an-

tiquity, that of Alexandria, so that most of the written learning of that and of previous ages was lost for all time. They did, however, form a valuable connection with the Hindu mathematics of their time, and appeared not only to have brought it to Europe, but to have assimilated it themselves to some considerable extent.

The origin of Hindu mathematics seems very uncertain. There is direct evidence of some accomplishment in a rule for finding $\sqrt{2}$ which is dated before our era, but their value for it seems to have been obtained much later. Their greatest contribution is our present number system, which came to Europe through the Arabs and hence got its name. From the seventh century it does not appear that they formed an independent school. Hindu mathematics seems to have been largely improved by the needs of astronomy. Their greatest exponents were Brahmagupta, who lived in the seventh century A. D., and Bhaskara, some five centuries later. Their work, again, is chiefly arithmetical. While the so-called arabic numbers were probably used by the former, the latter was the first who is known to have given a systematic treatment of the decimal system. Although the Arabs dispersed the western schools, they set up schools of their own which developed mainly on algebraical lines. One name stands out prominently, that of Alkarismi—who may be regarded perhaps as the founder of modern algebra—the name of the subject itself comes from him. But he used no complete symbolism, and he and his successors developed it mainly from the numerical point of view.

Chinese science seems to have started about the same time as that of Greece, but to have had little or no connection with our western science until the sixteenth century. Whatever mathematics the Japanese had probably came from China. It would appear at first sight that the earliest developments arose independently in all civilized nations about the same time,

speaking broadly, but our knowledge is so scanty that we can only say that the records nearly all date back to similar periods in each case. Whether there is anything significant in this fact must be left to conjecture.

With this brief sketch this era may be thought of as closed in so far as the development of science and particularly mathematical science is concerned. It witnesses a real beginning in the study of geometry and algebra and, to a much less extent, of physical principles. A system of logical reasoning was discovered which, in its main outlines, still forms the basis of all deduction at the present day. The properties of the simpler geometrical figures had been studied and committed to writing. The advance of arithmetic was hindered by a poor numerical notation, but the foundations were laid for future development by the introduction of the Hindu symbolism. Algebra had started to emerge from the rhetorical form of discussion into the more terse abbreviations which we now use. Astronomy never failed to have exponents, though many who doubtless desired to increase their knowledge were restrained by the superstition of the age and by ecclesiastical authority, which attempted to dictate the thoughts as well as the actions of men. In mechanics, Archimedes seems to have stood almost alone, largely, perhaps, because no scientific method in dealing with the fundamental problems of nature had yet become current amongst the learned men.

It is difficult to sum up in a phrase the reasons for the scientific hiatus which occurred during the following three or four centuries. The revival of learning which sprang up towards the close of the eighth century was almost barren of progress in mathematics. The schools established by Charlemagne, while teaching mathematics, developed interest in other directions. Reverence for authority appears to be the basis of nearly all the learning of the age and there is no more stifling attitude of

mind for progressive evolution of ideas. We may attribute this to a variety of causes any one of which may seem sufficient to explain it, but in reality, not one of them explains anything. It may perhaps be best likened to one of those pauses which nature seems to demand and in which breath is sought before taking the next forward step.

The first sign of activity found expression in the Crusades undertaken to free Jerusalem from Mohammedan control. Soon after this time, that is, at the beginning of the twelfth century, several of the modern universities were founded, partly as gatherings of students to learn and discuss, and partly as developments of schools which had been under the charge of the monasteries. The old Greek works on mathematics were revived and the learning transmitted by the Arabs began to be assimilated and taught. Systematic instruction and the writing of treatises for the transmission of knowledge were begun. These were mingled with courses on astrology, alchemy, and magic, perhaps, we may conjecture, because the learned man had little chance to earn his living except through supplying what was in common demand, and perhaps also because the ancient learning gave little enough scope for cultivation of the imagination.

A century later Roger Bacon appears on the scene. It is difficult to overestimate the man who, traveling over Europe and studying in Paris and doubtless absorbing the learning of his time, becoming a Doctor in Theology and a monk, could break away from his training and absolutely reject the ideas and methods of his age. One who could write that in order to learn the secrets of nature we must first observe, that in order to predict the future we must know the past, must certainly have had unusual clarity of vision. He taught too that mathematics was the basis of all science, but he clearly recognized that it could not replace experiment and knowledge of phenomena, but could be used to great advantage in deducing

results when the phenomena had once been observed: the point of view is thoroughly modern. But his three great works failed to have much influence on his times and seem to have been forgotten for several hundred years. Like many of his predecessors and followers in science, he suffered for his opinions.

The real start of modern science opens, as has been mentioned earlier, in the middle of the fifteenth century, and from this time on there is no break in the sequence of scientific discovery. We have also less need to relate its progress to that of the social order. While there have been periods in which wars have seriously disturbed the ability of nations to produce and to foster learning, there has been no time in the period in which the whole of the civilized world was so far involved in struggles that intellectual progress came to a stop everywhere. Moreover, all attempts since 1450 to enslave the world, either physically or spiritually, have ended in failure. It is true that five hundred years is comparable with the periods of Greek, Roman, and Mohammedan supremacy, but in each of these civilizations we see signs of decline in a far shorter period. At present there appears to be no indication that the crest of the wave of scientific progress has been reached. The world war just concluded, in its essence a struggle for liberty of thought and action, was far too short to submerge the knowledge of the existing generation and prevent it from being handed on to the next.

The period can be roughly divided into two parts, the two centuries until the time of Newton forming the first of these. It is chiefly characterized by a sustained effort to lay solid foundations for all those sciences in which mathematics is needed for development, and success, very nearly complete, was attained at the end of the seventeenth century. In astronomy and mechanics, Copernicus placed the sun in the center of our solar system. Kepler, building on the observations of Tycho Brahé, gave the laws of the planetary motions. Galileo laid

foundations for the study of mechanics and proved the rotation of the earth about its axis, besides making a host of astronomical discoveries with his telescope. In mathematics, the arabic numerals came into full use and were applied to the needs of daily life. The symbolism of algebra was completed in nearly the modern form used in elementary mathematics; much of the work done by Vieta, Cardan, and Tartaglia involved the solution of equations of the third and fourth degrees. Trigonometry, needed by the astronomer, the map-maker, and the navigator, was developed so far that Rheticus calculated a table of natural sines to every 10 seconds of arc and to 15 places of decimals. Logarithms were invented by Napier, and seem to have been adopted universally almost immediately. Descartes invented analytical geometry and thus gave to the investigators of space-forms a new weapon of immense power, while Desargues laid the foundation of projective geometry. Fermat, an amateur, but as able as any of his contemporaries, laid down many of the laws of numbers and founded the calculus of probabilities.

The brevity of this summary is not a measure of the achievements of these two centuries. For this we must look to those which followed. While, judged by modern standards, the actual progress seems small, it was far beyond that which had been achieved in all the previous ages. The only earlier contribution which has stood the test of time is perhaps the geometry of the Greeks, for the work of Archimedes, especially in mechanics, seems to have remained almost unknown up to the time of Galileo. The period showed not only a sound laying of foundations, but in its development of ideas, often only dimly expressed, showed that the germination of the seeds of future knowledge had already begun. Progress was frequently hampered by an unfortunate form of rivalry in which a discovery was kept back so that its possessor could propose problems to confute the claims for knowledge of his contempora-

ries. On the other hand, the circulation of knowledge was greatly increased by the possibility of printing old and new work. Books became regular articles of merchandise and could even be picked up in out of the way places.

The era of Newton is so important in the history of both pure and applied mathematics that no excuse is necessary for dwelling on what was achieved. If an attempt be made to characterize its results in a single sentence, it may be perhaps best emphasized as the epoch of the discovery of the fundamental laws of continuously varying magnitudes. Before this time such solutions of dynamical problems as had been obtained were isolated. Newton's formulation of the laws of motion and proof of the law of gravitation were found in his hands and in those of his successors sufficient to deal with all the problems of physics which were then and later under consideration. Little progress, however, could have been made without the necessary complement, the calculus, which permitted the study of varying quantities by symbolic methods. Rates of change, when uniform, presented little difficulty; the real problem was to deal with them when they were variable, as, for example, in the motion of a pendulum or the vibrations of a string. To a limited degree, the geometry of the straight line and the circle can deal with these questions, as Newton showed in the classic translation into geometry of his results for the motions of the moon. But his manuscripts indicate that he failed beyond a certain point to give geometrical proofs of other results obtained by means of the calculus.

But as I have emphasized before we must not only look to the applications, the chief question in Newton's time, but also point out that varying magnitudes have been studied for their own properties so extensively that they form the larger part of mathematical developments up to the present day. If we except the science of discrete numbers, it is only in comparatively

modern times that discontinuous magnitudes have received any extended study and even these have been advanced in many cases through developments of the calculus.

Isaac Newton seems to have been one of those very rare cases of genius breaking out without any very obvious stimulus from a particular teacher or school. His first introduction to mathematics was accidental: a book on astrology picked up at a fair in 1661 containing geometry and trigonometry induced him to study Euclid and then to continue by reading such textbooks as were available. His discovery of the calculus or "fluxions" as he called it, was made within three years and a half, the binomial theorem was formulated about the same time, and a year later he began his first attempts to prove the gravitation law. He was elected Professor of Mathematics in 1669, eight years after his entry into Cambridge as an undergraduate. At this time his chief subjects for lectures and investigation were optics and algebra, the former of which involved him in much controversy. In fact, all through his active period of work in mathematics, he seems to have suffered from the difficulties of having his great advances understood and accepted, although there never seems to have been much question amongst his contemporaries as to his wonderful powers. In 1679 he discovered the law of areas and showed that a conic would be described by a particle moving round a center of force under an attraction which varied inversely as the square of the distance. But it was not until 1684 that he began to work seriously at gravitation problems, his first step being the proof that a uniform sphere exerts the same attraction as a particle of the same mass placed at its center. From this time on progress was rapid. Within two years the manuscript of the *Principia* was finished and the following year printed.

The *Principia,* like most of the works of the time, consists partly of results previously known, but by far the larger part of it is Newton's own work. It begins with definitions, the

formulation of the three laws of motion and the principal properties which can be deduced from them, with some examples, forming an introduction to the first book, which contains his main work on gravitation. The second book is chiefly devoted to hydrodynamics and motion in a resisting medium and the third to various applications of the first book to bodies and motions in the solar system. As stated earlier, the proofs are cast into a geometrical form and freed from all traces of the method of fluxions which Newton had used to reach many of his results.

This great effort seems to have nearly exhausted his remarkable powers, for he produced little after its completion. In 1695 he accepted an appointment at the Mint and six years later resigned his chair at Cambridge. He was only forty-five when the *Principia* was published and he lived for thirty-eight years afterwards.

The half-century which followed the publication of the *Principia* seems to have been mainly occupied in understanding and digesting the advances made. On the continent, where Leibnitz's notation for the calculus was mainly adopted, a firm foundation was laid for the progress which began in the middle of the eighteenth century. In England the reverence for Newton was so great and separation from the continent so effective, that his methods dominated all the work for nearly a century and a half. This was perhaps mainly due to the translation of the *Principia* into geometry, which ensured its early acceptance but must have fostered a distrust of all results which could not be proved in the same way. And further, Newton's notation for fluxions, which did not bring out their essential properties, had great influence in preventing advances as against that invented by Leibnitz. Nevertheless, there are certain names in the English school which have lived to the present day. Brook Taylor, who was born in 1685, gave the fundamental series for the expansion of a function which is known by his name,

followed a little later by Colin Maclaurin with the particular case which is named after him. The latter also determined the attraction of an ellipsoid and introduced the idea of equi-potential surfaces. De Moivre, of French ancestry and birth, but a resident of England after the age of seventeen years, extended the use of the imaginary in trigonometry and thus prepared the way for the great development of the theory of functions of a complex variable which took place in the nineteenth century. Roger Cotes must also be mentioned if only for the high opinion Newton had of his abilities: he was only thirty-four years old when he died.

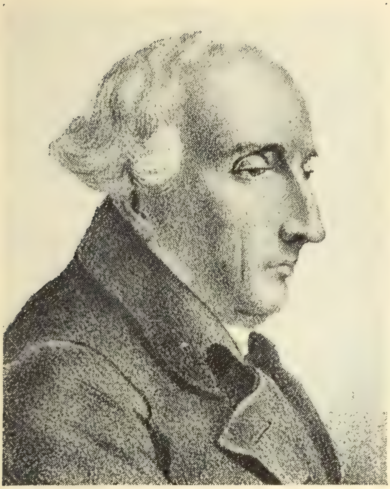
On the continent the Bernoulli brothers, friends and admirers of Leibnitz, were largely responsible for realizing the power of the calculus and making it known. They applied it to many physical problems, but perhaps their greatest influence came through their teaching abilities. Most of those in this period who achieved distinction were their pupils and several of their descendants were well known as mathematicians during the eighteenth century. But the most able men of this period were undoubtedly Clairaut and d'Alembert. The former produced the first theory of the motion of the moon developed from the differential equations of motion: in it he showed that the theoretical motion of its perigee, which in the *Principia* was obtained to only half the observed value, agreed with observation when we proceed to a higher approximation. There was an interesting development in this connection. Clairaut at first thought that it would be necessary to make an addition to the Newtonian law in order to produce agreement, and it was only when he carried his work farther that he saw such an addition to be unnecessary. A similar addition was examined by Newcomb and others as a possibility which might explain the deviation of the perihelion of Mercury from its observed value, and it is only within the last five years that such an addition has been deduced from the relativity theory by Einstein.

Clairaut also obtained the well-known formula for the variation of gravity due to the shape of the earth.

D'Alembert is best known by his work on dynamics, in which he showed how the equations of motion of a rigid body could be written down: the principle is still known by his name. He also reached the well-known wave-equation, a partial differential one of the second order, in several physical investigations and showed how a solution may be obtained. This was pioneer work but its further development was not carried forward to any extent by him.

The great period of continental activity which began in the middle of the eighteenth century and contained the names of Euler, Lagrange, Laplace, and many others of whom a brief mention only can be made, was characterized also by social ferment which has profoundly changed the basis of society. The French revolution with all its far-reaching consequences took place in the middle of the time of greatest mathematical activity, and the Napoleonic wars, carried into almost every country of Europe, served to stir up intercourse between the nations to a degree which must have had much effect on all forms of scientific activity. At the same time, the American revolution produced a new body of political thought which has had its development in the formation of a great and powerful nation. In England, comparatively free from invasion or social disturbance, little was produced of permanent value, the influence of Maclaurin being directed to the retention of published Newtonian methods. With the exception of the Italian Lagrange and the German Gauss, the great names of the period belong to France and Switzerland.

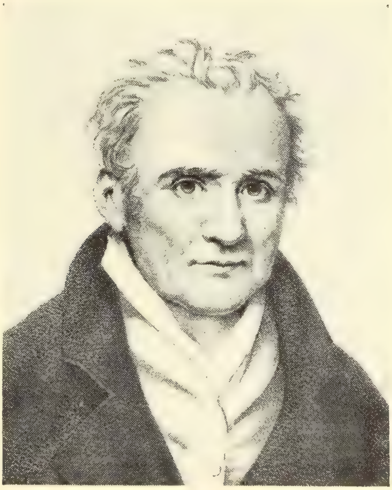
Those who have had the most far-reaching influence, judged by modern standards, besides Euler, Lagrange, and Laplace, are Legendre, Fourier, Poisson, Monge, and Poncelet. I omit those whose chief labors were more closely associated with experimental work. The means for publication in this period



Joseph Louis Lagrange.

Jean Bernoulli.

Simeon Denis Poisson.



Gaspard Monge.

were becoming more extensive and it is less easy to discover what each man owed to personal meetings with his contemporaries. The principal academies of Europe were starting or had started their volumes of transactions, extended treatises could be published and circulated, and the scientific men had new opportunities to meet and discuss, even to some extent with those of other countries, especially on the continent. The more enlightened courts sought the services of the ablest scientific men and, when the latter did not mingle too much in politics, on the whole treated them well. Fortunately, at least for the leaders, their teaching was usually confined to small bodies of earnest students and they appear to have been little hampered by demands on their time and energy for administrative duties. It is interesting to note that in a time of political disturbance which was perhaps comparable to that produced by the great war, the main foundations of modern mathematics, both pure and applied, were firmly laid.

Leonard Euler, born in 1707 at Basle in Switzerland and educated in mathematics by Bernoulli, was perhaps more industrious than any of his contemporaries and it is difficult to say whether his services to mathematics are to be judged best by his excellent treatises on analysis, including the calculus, or by his original memoirs on applied mathematics. In the former, he followed up all that was known at the time, recasting proofs and setting the whole in logical order. In the latter, he is best known for his formulation of the equations of motion of a rigid body, for a similar service in the equations of motion of a fluid, and for his work on the theory of the moon's motion. With respect to the last it may be said that every modern method of treatment can be found to have started with Euler. He continued his work to the end of his life in 1783 in spite of losing his sight some fourteen years earlier and his papers by a fire in 1777.

J. L. Lagrange was born at Turin in 1736 and was, like

Newton, practically self-educated as far as his mathematical studies were concerned. It gives some insight into the comparatively small body of mathematical literature at the time he was seventeen years old and his own great ability, that an accident directed his taste for mathematics and that after two years' work he was able to solve a problem in the calculus of variations which had been under discussion for half a century. At the age of twenty-five his published work showed that in ability he had no rival. Before his death, at the age of seventy-seven, he had left his influence on almost every department of pure and applied mathematics. His generalizations of the equations of mechanics have proved to be fundamental in all modern investigations and his applications to dynamical theory of the principle of virtual work and of the calculus of variations are now even more important than at any time in the past. The latter is applied not only to particles and rigid bodies, but also to fluids. To celestial mechanics he contributed several new methods on both the theoretical and practical sides of the subject in which are developed such topics as the general problem of three bodies, stability of a planetary system, mechanical quadratures, and interpolation. In pure mathematics his lectures on the theory of analytic functions, afterward expanded in treatises, form the basis on which later writers built. He also founded the science of differential equations by considering them as a whole rather than a treatment of such special equations as might arise in particular problems. And he contributed some important memoirs on the theory of numbers. His influence was undoubtedly much increased by a remarkable gift of exposition both in lecturing and writing: those who have read his *Méchanique Analytique,* in which his most important dynamical contributions were placed, will appreciate this fact. And this may be said independently of the fact that he had a simpler problem before him than has the modern mathemati-

cian with the enormous mass of past work which he has to consider and the selection which must necessarily be made.

P. S. Laplace, whose mathematical ability is unquestioned, was essentially an applied mathematician in that he devoted himself almost entirely to the solution of the problems of nature by mathematical methods. In general, he was not particular about mathematical proofs or logic, provided he could obtain results: in many respects he may be said to be the founder of the more modern schools of mathematical physicists. His most enduring work has proved to be in the theory of attraction, especially gravitational, and its application to the solar system. He made potential a real and valuable instrument of analysis and discovery, working out many of its properties, and applying it in various directions. The famous second order differential equation $\triangle^2 V = 0$, which is satisfied by every gravitational arrangement of matter, has been used as a substitute for the simpler expression of the Newtonian law of attraction and is especially interesting at the present time, since it may be regarded as the Newtonian analogue of the Einstein law. Laplace was the first to attempt a complete explanation of the motions of the bodies of the solar system, or at least to formulate methods which could be applied for this purpose, and his *Méchanique Céleste* remained the standard work of reference in this subject for a century. The theory of the development of the solar system from a primeval nebula which goes by his name and which was independently set forth somewhat earlier by Kant, has never been entirely rejected, although its supporters have often changed it almost beyond recognition while retaining his name in connection with their work. Its fundamental idea consists of the contraction of matter under gravitational attraction, but few now believe that the matter can produce planets and satellites by the throwing off of concentric rings as he supposed. What he did for celestial mechanics, he also achieved for the subject of probability, his

Théorie Analytique des Probabilités being the classic treatise in which the whole is put on a sound basis and developed in various directions. It must be added that he gave many theorems and results in pure analysis but in most cases these were invented to solve physical problems.

Of the remaining names in this period, Legendre was essentially an analyst, his work being mainly in the theory of numbers, which few mathematicians of this time altogether left alone, in integral calculus, and elliptic functions. His treatises on these subjects are still consulted. Monge and Poncelet may be regarded as the founders of modern descriptive and projective geometry respectively. Fourier, in his *Théorie Analytique de la Chaleur,* enunciated the theorem for the expansion of a function in a periodic form which has had such immense value in the discussion of all periodic phenomena, and has now a literature of its own. Poisson's work in attraction is on similar lines to that of Laplace, whose natural successor he seems to be.

It is convenient to view the progress made in the nineteenth and twentieth centuries from two points of view: one, the development of the three great branches of mathematics, geometry, analysis, and their applications to other studies; the other, the development of new ideas which have applications in many branches of mathematics. While it may be said that the former is more particularly characteristic of the first half of the nineteenth century and the latter of the succeeding period, it would give a false idea of the method of progress to regard these as anything more than general tendencies. But the difficulty (mentioned earlier) of conveying an understanding of the advances made in pure mathematics, even by one much more familiar with them than the writer, occurs in an exaggerated form in attempting a chronicle of the work of the past century. The task is far easier in applied mathematics, because most of us

have some acquaintance with the problems, and the ideas to be conveyed are not so far away from our everyday experience. Consequently, in the former I can do little more than point to a signpost here and there, occasionally indicate the course of the road which has been followed, or describe by an analogy or an example a result which has been obtained.

The older geometry, which consisted in the investigation of figures which could be generated under some simple descriptive definition like lines, circles, or conic sections, was greatly extended by Descartes' invention of analytical geometry. In the latter an algebraic statement of the properties gave rise to various classes of curves which could be ordered according to the forms of algebraic statement. Their properties could be investigated with much greater ease. The way was opened also for the consideration of the different kinds of curves or surfaces which possessed some definite general property; the properties common to a given class of curves or surfaces; the relations which may exist between theorems in analysis and geometry; and so on. When the methods of the calculus were added, the range of investigation was again widely extended through its facility for dealing with the properties of tangents and curvature. The new results obtained were undoubtedly instrumental in stimulating investigation from the more purely geometrical point of view. The names of Desargues, Monge, and Poncelet have been already mentioned as the creators of the subject of projective geometry; their work was continued and, during the third decade of the nineteenth century, developed into a separate branch by Moebius, Plücker, Steiner, and a host of writers who have followed them. Simple illustrations of the idea involved are that of map-making, in which we represent portions of the spherical surface of the earth on a plane, and that of the shadow of a figure cast by a ray of light. These simple ideas have been generalized by considering the

common properties of figures which are projected according to some given law and more generally by correspondences between two or more figures. Another development is that of transformations which leave properties unchanged. It will be seen at once that measurements of actual lengths of lines or metric properties, as they are called, are not those which would ordinarily be unchanged by projection, but this difficulty was overcome by Laguerre, Cayley, and their successors.

Differential geometry is in its essence a study of the properties of geometrical figures by investigating the properties of small elements of those figures. Such properties as curvature of a single curve or surface, and those which depend on classes, such as the envelope of a system of curves, the surfaces which cut systems of surfaces at right angles, are the natural subjects of investigation under this head. In 1828 Gauss published a memoir which immensely extended the range of this subject, by introducing new ideas which have been applied to such topics as the deformation of surfaces under given conditions and more particularly to those properties which remained unchanged by deformation. The subject is closely allied to many problems in physics.

Many futile attempts to deduce the axiom of parallels from the other axioms laid down by Euclid led Lobatchewski and Bolyai to see what would happen if a geometry free from this axiom were constructed. The results showed that it could be made quite consistent in all its theorems, that some of the Euclidean theorems would still hold while others would be changed or generalized. Their chief successor was Riemann, who showed that all previous geometries were special cases of a more general system. In our own time the subject has been developed in the direction of finding the properties which are possessed by the different geometries and also by investigation of the different sets of axioms which can be used as a basis for constructing different classes of geometries. In the applications

to physics the most important has been perhaps the recognition that our own space is not necessarily Euclidean and that we can only find out its nature by examining properties which we are able to observe and measure.

The new developments have not prevented further research on the older lines. Geometry is still much used as a convenient language for the development and expression of analytical results. As seen below, the plane is the home of the complex variable, but in the theory of functions of this variable, it has become many-storied with ladders reaching from one story to another. Most of our physical problems, however, demand the use of three dimensional space and here the complex variable is not sufficient, because with our ordinary algebraic rules there are only two different kinds of numbers, the real and the imaginary, which are used to deal with two different directions in a plane. Hence the theory of vectors, which deals with straight lines in any number of dimensions, and particularly three, has been evolved and is coming more and more into use on account of its brevity and compactness. It requires, however, a new notation to be learned and a certain degree of familiarity with the operations which are possible.

The older theory of numbers in general dealt with integers and to a less extent with fractions, square roots, etc., that is, numbers which could be formed out of the integers by the ordinary operations of arithmetic. Gauss opened the way to a more extended idea of the meaning which might be attached to numbers by introducing those which are the solutions of an ordinary algebraic equation of any degree, whose coefficients are rational; such numbers are called algebraic. They naturally introduced complex numbers and have properties such as divisibility more extended than those which play a large part in our ordinary number system. This soon demanded a theory of congruences, which, in their simplest form, are numbers which, when divided by a given factor (called the modulus),

always leave the same remainder (a residue). The theory of forms was another development which arose. Since Gauss' time these ideas have been greatly extended to many other kinds of numbers in which special classes have special properties, and these classes are the main subjects of investigation.

The extensive development of the theory of functions of a complex variable is perhaps the most significant achievement of the last hundred years. The imaginary was always arising in such questions as the solutions of quadratic equations and in the new branches. The next step was to give a geometric interpretation of a complex number by showing that it could represent in a single symbol the two coördinates of a point in a plane. A function of a complex variable was therefore a function which could take values over an area, as against one of a real variable, which could only take values along a line. The majority of functions become infinite for one or more values of the variable and these infinities play the major part in the development of the theory. To Cauchy belongs the honor of starting the work in the third decade of the nineteenth century, examining such questions as the possibility of developing such functions in series, their integrals, and the actual existence of functions of different kinds. Closely following him, Weierstrass and Riemann developed Cauchy's ideas, the former by basing his arguments on a special form—a series of powers of the variable—and the latter by using geometrical and even physical ideas for progress. Their successors have merged these different modes of development and have continued to investigate with success the representation of a function under given conditions, and the limitations of a given function. At the same time special functions, particularly those known as elliptic, were being developed by Abel and Jacobi, and the latter extending them in a very general manner. We have now many groups of such functions, some of which have

Arthur Cayley.

Jacob Steiner.

Karl Friedrich Gauss.

Augustin Louis Cauchy.

become of sufficient importance to have whole treatises devoted to them.

The study of functions of real variables during the past half-century has been largely due to the critical spirit which has compelled mathematicians to examine thoroughly the foundations of the calculus. It consists of "all those finer and deeper questions relating to the number system, the study of the curve, surface and other geometrical notions, the peculiarities that functions present with reference to discontinuity, oscillation, differentiation and integration, as well as a very extensive class of investigations whose object is the greatest possible extension of the processes, concepts, and results of the calculus."[1]

Ever since the invention of the calculus, the relations between two or more variables which contained also their derivatives, that is, differential equations, have been continually brought before the eyes of the mathematician by the physicist, owing to the fact that the simplest symbolic statement of nearly all physical problems has been in the form of one or more differential equations. For finding the derivatives or integrals which arose in his work, definite rules were generally available, even if they demanded much calculation. But he failed to find such rules for most of his differential equations, and in fact they do not exist. The pure mathematicians, led by Cauchy, took up the question from other points of view, asking, in particular, the nature of the function which is defined by a differential equation. This is naturally an extension of the theory of functions, and the methods of the latter opened the way. But the questions are so difficult that only a particular form, known as the linear, has made any considerable progress; this form, however, does embrace a large number of the functions whose properties had been examined. In

[1] J. Pierpont, Bull. Amer. Math. Soc., 1904, p. 147.

our own generation the subject has been extended by the consideration of equations in which integrals also occur; these again are necessary in certain physical problems.

Most of the progress which has been made in applied mathematics will be treated in the chapter on Physics, but in addition to the remarks at the close of this article some few words may be said of those branches in the development of which mathematics plays the larger part. The chief of these is the dynamics of a system of particles and rigid bodies. W. R. Hamilton and C. G. J. Jacobi, in the second quarter of the century, put the equations of motion of all such systems into forms which not only permitted of remarkable generalization, but indicated new methods of integration which opened out research into the general properties of such systems. The later work has been mainly developments and applications of these methods. The particular branch of this subject known as celestial mechanics has been continued on the practical side by extended theories of the motions of the planets and the moon and on the theoretical side by investigations into the general problem of three or more bodies. In the former, numerous writers have continued with increasing accuracy the work of the eighteenth century: for the latter new foundations were laid by Poincaré some thirty years ago.

Hydrodynamics has had less success in its applications. The prediction of the tides, chiefly from the work of G. H. Darwin, and the relative equilibrium of liquids in rotation, by him and Poincaré, have advanced in a satisfactory manner; but the knowledge of the motions of bodies in actual fluids is still in an elementary condition, especially when an attempt is made to apply it to under-sea and air craft. This, of course, refers, not to the experimental side, but to developments from the equations of motion. An interesting, but now almost neglected, subject is that of vortex rings in a perfect fluid, the main features of which were given by Helmholtz and Lord Kelvin,

giving rise to a hypothesis, now abandoned, that the fundamental atoms of matter consisted of such rings. The motions of our atmosphere have so far defied attempts at explanation on any general plan. The theory of sound, on the other hand, in the hands of Helmholtz and Lord Rayleigh, has been well developed. The theory of elasticity is almost entirely a creation of the present century and has found many applications.

Many of the ideas which are now fundamental in mathematics have had their origin in an attempt to advance some particular branch. Development has proceeded to a certain stage by means of known methods and then stops, owing perhaps to mathematical difficulties or to a failure of those methods to cast further light on it. A new method of attack has then been evolved, showing new roads by which it may be explored, after a time leading to openings which enable the investigator to continue on the earlier lines. These new methods have then been seen to be applicable to various other branches, thus forming connecting links and shedding new light. Indeed, one not infrequently meets with a statement that all mathematics can be based on some one of these ideas. This may be true, but progress demands that the subject be cross-cut in many ways: a new country may be opened out by one great highway, but it is only well developed by several main roads in different directions with numerous connecting branches. I shall take up certain of these ideas and try to indicate briefly their bearing on various mathematical topics.

Some illustrations have already been given of the effect which a critical examination of the logical processes used in mathematics has produced. In geometry, the examination of Euclid's axioms has led to the discovery of ideas of space other than those which were current in earlier times. In analysis, algebras have been constructed in which some of the familiar rules have been dropped or changed. The way was thus

opened for the examination of the foundations on which mathematics rests. Here the work gets close to a consideration of the mode in which the human brain can think. But without going into this question it is possible to indicate the general method followed at the present time. At the outset a set of statements, usually called axioms or postulates (there is a difference of opinion as to the exact meaning to be attached to these words), is made. These statements may be redundant but must not be contradictory: a complete system is one which contains all the statements necessary for the object in view but which has nothing unnecessary or redundant so that no statement or combination of statements can result in another of the set. To connect and deduce, a system of reasoning is also required. From this it will be seen that mathematical science has no necessary relation to natural phenomena, but that it can be regarded as solely a product of the brain and that its results are simply consequences which may be deduced from ideas without external assistance. The last half-century has seen great progress made in clarifying our ideas and in the introduction of rigorous methods of argument. It has now extended to the phenomena of nature, particularly in the direction of a reconsideration of our ideas of time and space and in an examination of our powers of observation, as will be illustrated below.

The idea of invariants has permeated every branch of pure and applied mathematics. In its elementary forms it is not difficult to understand. Natural processes are subject to change, but we can nearly always find certain features of them which seem to remain the same in the conditions under which we observe them, as, for instance, mass and energy. In geometry, the ratio of the circumference of a circle to its diameter is constant, the ratio of the sections of any system of straight lines cut by three parallel lines is the same, certain properties of a system of curves remain unchanged under given conditions of de-

formation, and so on. In analysis, one of the commonest modes of investigation is to find out what expressions remain unchanged when a specified change is made in the symbols. It has been said that all physical investigations are fundamentally a search for the invariants of nature. The various terms which occur in modern algebra, such as discriminant, Jacobian, covariant, are special forms of the same fundamental thought.

The idea of permutations and combinations which few of us fail to meet with in our everyday experience, was chiefly developed in earlier times from the point of view of the number of arrangements which could be made of a set of objects under certain specified conditions. The modern theory of groups is the natural successor of this subject, but as has so often happened, the point of view and its development have changed. If we have a set of symbols and replace one by another according to a specified law, we can consider what changes will leave unchanged certain combinations of those symbols, as well as the number of such changes which can be made. In doing this we naturally make a connection with the theory of invariants. Such a set of changes is called a group. But a more fruitful idea has been obtained by considering what combinations amongst the symbols, using a specified law of combination, will always produce another of the symbols, and will produce nothing else. As a simple and familiar example, take the series of numbers 0,1,2, . . . with the law of addition. If we add any two of these numbers we always get another of the same series and we never get any other kind of number. The whole of the series is called a group from this point of view. The even numbers form a sub-group under this definition, but the odd numbers do not, because the sum of two odd numbers is not an odd number. If we use the same series, omitting the zero, with the law of multiplication instead of that of addition, we again have a group, but now the odd numbers form a sub-group. Again we may consider the operation of turning a straight line through

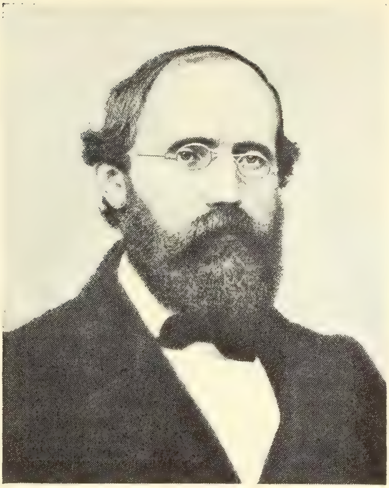
60° in a plane about one end of the line. There are obviously six positions of the line and in whatever one of the six positions we start, a turn through 60° will always give one of the other positions. The whole set constitutes a group.

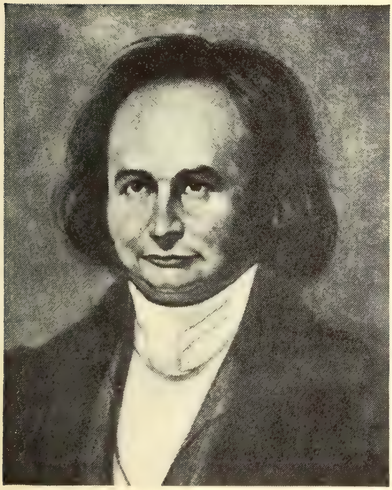
The idea of a group of substitutions enabled Galois and Abel, before the middle of the nineteenth century, to open up the way to treat algebraic equations of a degree higher than the fourth, and in fact to show that the methods used to solve equations of the second, third, and fourth degrees could not in general be applied to those of the fifth and higher degrees. The quintic had long been a puzzle to mathematicians, all attempts to give a general solution in terms of radicals having failed. Later on, Sophus Lie applied the idea of groups to the solution of differential equations and was able to indicate the nature of the solutions in certain general classes. Before his time the methods for finding them had been disconnected and apparently without any common property. Another form of the group theory has been applied with success to the investigation of curves and surfaces and it is not too much to say that the idea has been one of the most fruitful in producing progress. "When a problem has been exhibited in group phraseology, the possibility of a solution of a certain character or the exact nature of its inherent difficulties is exhibited by a study of the group of the problem."[2]

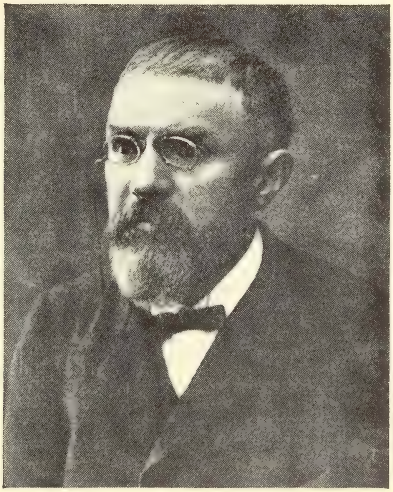
One of the most useful efforts of the nineteenth century mathematicians has been in the direction of proving the possibility or impossibility of performing certain operations or of solving certain problems, that is, in the investigation of existence theorems, as they are often called. The squaring of the circle or the trisection of an angle are two of the oldest of them and later arose the problem of obtaining a finite numerical expression for the number *e* which is the base of

[2] Dickson, L. E., Paris International Congress, vol. 2, p. 225.


Hermann Minkowsky.


Bernhard Riemann.


Karl Gustav Jacobi.


Henri Poincaré.

the Napierian system of logarithms and which arises in numerous mathematical and physical investigations. The failure of attempts to solve these problems finally led mathematicians to consider whether they could not be proved to be insoluble under the conditions laid down. Complete success has rewarded them. We now know that with the use of the ruler and compasses alone it is not possible to find a square which shall be exactly equal in area to that of a given circle, nor given any angle is it possible to construct the lines which shall divide it into three equal parts. The number e, too, cannot be exactly expressed by fractions or square roots or any other such simple numerical representations, though it can be approximated to as closely as we wish by decimals or in other ways. The labor of useless effort on the part of the mathematician is thus avoided, though we shall still probably continue to hear of those who claim to have performed the impossible. In our time it is quite usual as a part of an investigation to find included in the construction of some new function or in a new representation of a known function a proof of its existence; especially in those cases where the possibility may be called into question. In celestial mechanics an important part of Poincaré's work consisted in proofs of the existence or non-existence of different kinds of motion and of different kinds of integrals. Indeed, we have a considerable class of literature which consists solely in demonstrating the existence of functions or curves with little indication of the methods by which they may be constructed. The stimulating value of such researches in suggesting problems is often forgotten by those who, with some justice, complain of their dullness.

It is strange, in connection with existence theorems, that some of the problems, most simple in statement, are still unproved. Long ago Fermat stated that there are no whole numbers which will satisfy the statement that the sum of the n^{th} powers of two whole numbers is equal to the n^{th} power of a third

whole number, except when n is equal to 2. This impossibility has been proved for all values of n up to 100 and for a few beyond, but no general proof has yet been given that it is universally true. Again, there is no general method which will enable us to pick out the prime numbers, that is, those which are not divisible by any other number except unity. In geometry we have the famous four-color problem in which it is desired to prove that a map consisting of countries of any shape and arrangement can always be painted with four colors so that no two adjoining countries will receive the same color. In these and similar cases, no exceptions to the statements have been found and there exist no complete demonstrations of their possibility or impossibility. It is of course assumed that if they are true a proof can be constructed without a change of our axioms concerning number or space.

It will be seen from the sketchy remarks of the last few paragraphs that at least one outstanding feature of pure mathematics during the last century has been its emancipation from the trammels imposed by any necessity for application to physical problems. It is, nevertheless, necessary to say a few words about these applications, although the major part of the story naturally comes under the history of physics. Under the general term "applied mathematics" are included at least three methods of study. In the first and simplest, we translate the physical problems into symbols and deduce the consequences we desire by mathematical methods. The work consists, therefore, of little more than an argument on lines laid down by the mathematician. In the second, a study of the formulæ and relations which have arisen from physical problems is made, without any special desire to apply them to the phenomena: as indicated above, much of the pure mathematics arose in this way, even before it was recognized that such study was a quite legitimate intellectual exercise. In the third, the mathematical processes used by the applied mathematician

are studied in order to find out their limitations, the extent of their validity, what extensions they will admit, how more general methods may be obtained, the best manner of treatment, and so on. This is not by any means an infertile source of progress, as may be illustrated by Poincaré's work on the divergent series which are used to calculate the places of the moon and planets.

The most fundamental change in the attitude of applied mathematicians has been in the recognition and working out of the consequences of simple fundamental principles or laws. Foremost amongst the latter is that known as the conservation of energy, brought into prominence in the middle of the nineteenth century by the labors of Helmholtz and Kelvin. It is now regarded as the chief invariant of the universe and has been applied to every branch of physics. Owing to the various forms which energy can take and to the fact that we are practically compelled, in applying mathematics to a physical problem, to deal only with some partial phase of it rather than with the whole, we cannot always assume that the principle holds in a particular problem. But in the majority of such cases the energy which is lost or changed from the particular form which we are considering is small, so that this loss may be neglected or allowed for. When the loss is zero, the differential equations of the problem admit of an integral which expresses this fact. Newtonian mechanics leads to two forms of energy, kinetic (that due to motion) and potential (that due to position), and the development of the mathematics of all material systems has been mainly based on this separation.

The principle of Least Action, enunciated by Maupertuis in 1744 but first put into correct mathematical form by W. R. Hamilton a century later, is essentially one which demands mathematical treatment. The action of a system is a certain function depending on the velocities and relations of its parts which takes a minimum value whenever the system moves

under natural laws. The process of discovery of this minimum leads to the differential equations of motion of the system and thus includes a complete statement of the problem. Since the initial form of the function is an integral, its mathematical treatment consists in finding the least value of this integral and thus becomes a problem in the calculus of variations to which considerable attention has been given by pure mathematicians, especially during the last two or three decades. While the physical consequences of the principle have been less developed than those of energy, there appears to be a growing feeling as to its fundamental importance and the aid of the mathematician in solving the problems which it raises will become increasingly necessary.

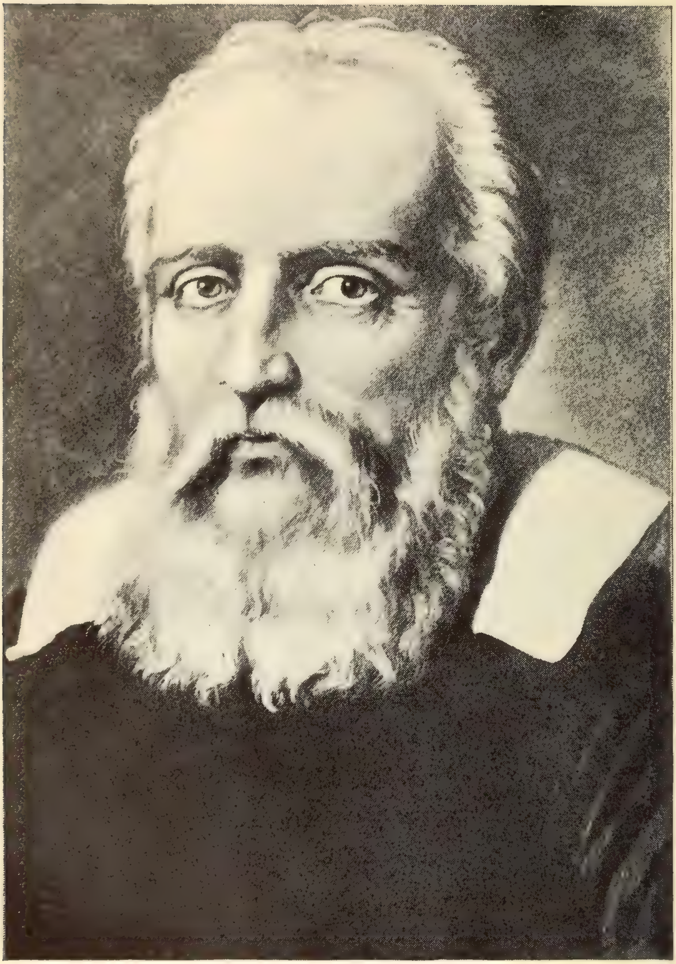
The study of the properties of a system containing a large number of particles not fixed relatively to one another, now generally studied under the term "statistical mechanics," has penetrated into several branches. It is to be understood here that the question is not one of finding the separate motions of the various particles but of trying to find out such properties of the system as can be deduced from averages. It is probable that as long as we cannot observe the motions of the separate particles, we should be able to deduce in this way most if not all the properties of the system that we are able to observe. Maxwell and Boltzmann founded the subject from this point of view, applying it to the kinetic theory of gases, while J. W. Gibbs was largely responsible for its application to thermodynamics. In astronomy the present century has seen it applied to the motions and positions of the stars, thus opening the way to a knowledge of the outlines of the construction of the stellar universe. Mathematically these questions are obviously very similar to those parts of probability which deal with errors of observation and thus form a continuation of the development of that subject.

The mathematics of continuous media has received very

complete development during the century and, besides the earlier investigations into the motions of fluids and elastic solids, has been applied to the so-called luminiferous ether and finally by Maxwell to the whole electric field. In all this work the continuity of the medium is a fundamental axiom involving the hypothesis that no action can take place without its presence. Further, the Newtonian laws of motion were assumed as fundamental and time and length were regarded as unchangeable separate entities. The classic experiment of Michelson and Morley, which showed that the velocity of light was apparently independent of the velocity of the medium in which it traveled, and observations on the motions of certain particles with very high velocities started a reconstruction of ideas. It was possible to explain the results on the assumption that the length of a body depended on its velocity. It was then that Einstein sought to generalize Newton's equations of motion by making them entirely relative, not only for uniform velocity, but also for accelerated motion. By adding the assumption that the laws of nature should refer to all such systems of reference and by making the velocity of light a fundamental constant of nature, he was finally able to generalize the whole subject. Matter appears simply as a form of energy. Gravitation can be exhibited as due to a warping of space without the introduction of force, but if this is so, the Newtonian law requires a minute correction. The motion of the perihelion of Mercury and the bending of a light ray as it passes near the sun have given remarkable confirmation of this theory. His work crosscuts several subjects which previously had an interest only for the pure mathematician, in particular the theory of extensible vectors (tensors) and the theory of invariants. His differential equations for the gravitational field should supply mathematicians with problems of great difficulty and interest for some time to come. Those for the electric field are unchanged. A further interesting product of this work on rela-

tivity lies in the question of what we can or cannot observe and in what may be deduced from observation without the assumption of hypotheses. This is, of course, fundamental in all experiments, but it has received little attention as an exact science. Given that we can only observe certain properties of a function, what limitations is it possible to make in the construction of the function?

Finally the quantum theory of Planck, according to which energy is not infinitely divisible but is always received or emitted in exact multiples of a fundamental unit, is bringing forward the necessity for a calculus allied to that of finite differences as against the differential and integral calculus which depends in general on continuity. It is even suggested that not only energy, but also space and time have ultimate parts which cannot be divided. At present the mechanics of this theory is in a very nebulous state, but as a statement of the results of observation it has had very considerable success. The construction of the atom is now generally exhibited as a kind of minute solar system, but there is as yet no indication how such a system can only permit of the limited number of motions required by the quantum hypothesis. It may perhaps be due to fundamental instabilities, for we know little of the ultimate stability of most of the motions in the problem of even three particles. In any case, the field of work has approached one of the oldest of mechanical problems and the reaction of celestial mechanics on that of the atom should prove stimulating to both.



GALILEO GALILEI

CHAPTER II

PHYSICS

By HENRY ANDREWS BUMSTEAD

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THE beginnings of anything like a connected history of the science which is now called physics may be placed with considerable definiteness about the beginning of the seventeenth century and associated with the great name of Galileo. It is of course true that innumerable isolated facts had been known for many centuries which are now included among the data of this science; and many tools and simple machines which are now regarded as applications of physical principles had been devised and used. Even prehistoric man knew some of these—to his very great advantage. But, with one important exception which will be mentioned later, there was, in the ancient world, no connected body of knowledge in this field which can properly be called scientific. In this respect physics differs radically from mathematics or astronomy, natural history or medicine, each of which began its modern career with a store of scientific knowledge that had been obtained and put in order before the Renaissance.

The reason for this difference is doubtless to be found in the fact that the progress of physics is dependent, almost from the first step, on the method of experiment as distinguished from the method of observation. For some unknown psychological reason, the appreciation of the possibilities of experiment as an intellectual tool and the ability to make use of its

technique appear very late in the history of human development. A few individuals like Archimedes understood and practiced it, and it is difficult to understand why the seed which they sowed proved sterile. Certain inhibitions, common (despite their very different temperaments) to the Greeks, the Romans, and the men of the Middle Ages, seem to have prevented the infection from spreading from its original foci. I have no theory to offer as to the cause of the removal of these inhibitions during the sixteenth and seventeenth centuries; but whatever the cause, we must, I think, recognize that about that time a new factor made its appearance in the intellectual world which has survived and grown and has produced momentous results.

Some no doubt will be disposed to question the novelty which I have attributed to the methods used by Galileo and his successors. They will say with truth that men have been experimenting since long before the dawn of history; that by this means they improved their weapons, food, clothing, shelter, and means of transport, so that the enormous advantage in material surroundings which the Roman of the Augustan Age had over the prehistoric cave dweller may properly be said to be the result of a long course of progressive experimentation. But what I have, for the sake of making a distinction, called the experimental method in science is a very different thing from the slow empirical improvement of tools and appliances which went on before the beginnings of the modern era. The two kinds of activity differ fundamentally in the objects which they seek to attain and in the means they adopt for the accomplishment of their purposes.

The difference of objective is well illustrated by a remark of Galileo's at the very beginning of one of his most important works, the *Dialogue Concerning Two New Sciences*. He says that he has long thought that the workmen in a great shop such as the Arsenal at Venice must know many things which

would be of great service to philosophers if they could only be persuaded to use them. And he does in fact take such workman's knowledge, got by the old empirical process, and employ it for a purpose for which it had never been used before; to find out, for example, something about the laws and regularities governing the strength of materials and their dependence upon the size and shape of the object considered. The knowledge thus gained might or might not be useful to the workman, but it was of great consequence to the philosopher. Every scientific experiment has an objective of this kind—that is, every one that can properly be called an *experiment,* that has in it an element of originality and adventure into the unknown and that is not a mere routine test by known methods. Its purpose is much more general than the improvement of a tool or a telephone; and because of its generality it may incidentally do more to improve implements and technique in widely diverse fields of industry than thousands of experiments of the old cut-and-try kind extending over many centuries. The geometrical rate of increase resulting from this is sufficiently obvious from the industrial history of the past hundred years. Its continuance, however, is strictly conditioned upon the retention of the attitude of Galileo's philosopher; he may glance out of the corner of his eye at the by-products of his work, but he must not think too much of them and must keep clearly in view his own philosophical mission.

As I have said, the modern experimental method differs from the older empiricism in procedure as well as in purpose. The actual experiment is only a part of the process and does not come first in order of time; before it can be begun advantageously there must be much careful thought and planning, which often involves mathematics and deductive reasoning of the most old-fashioned kind. But there are no artificial hazards and rules of the game, such as those which the Greeks were so fond of imposing in mathematical problems. Any sort

of logic (or the lack of it) is permissible, since the final test is to be the experiment and not consistency of argument; it will indeed be a test of the premises no less than of the reasoning process. The greatest masters are those who make most use of apparently non-logical processes—intuitions and "hunches" which are perhaps the results of subconscious reasoning from data but dimly perceived.

The experiment itself is an observation made under highly artificial and carefully prearranged conditions, and it is this which gives the method its greatest advantage over simple observation of natural phenomena. This is well illustrated by Galileo's work upon the principles of mechanics and in their application to the particular case of the motion of falling bodies. Centuries of inescapable observation of moving bodies had led to no correct idea of the simple laws underlying their behavior, because these laws had been obscured by the effect of friction—a secondary condition of the problem. Galileo's experiments consisted in reducing these effects until the true nature of the phenomena could be observed. The famous experiment at the Leaning Tower of Pisa was a spectacular demonstration of one point of his theory designed to confute his Aristotelian critics; but the really important and fertile experiments were quite simply arranged with the help of iron balls, inclined tracks, boards, nails, and bits of string. With the simplest material means he laid the foundations of dynamics and, with it, those of physical science as a whole. Lagrange remarks that Galileo's contributions to mechanics "did not bring him in his lifetime as much celebrity as those discoveries which he made about the system of the world, but they are today the most enduring and real part of the glory of this great man. The discoveries of Jupiter's satellites, of the phases of Venus, of sun spots, etc., needed only telescopes and assiduity; but extraordinary genius was needed to disentangle the laws of nature from phenomena which are always

going on under our eyes, but of which the explanation had always eluded the search of philosophers."[1]

The world was ready for the structure which was to be erected upon the foundations laid by Galileo. In the next generation, Torricelli in Italy and Pascal in France showed by bold reasoning and experimentation that Nature's *horror vacui* was due to the weight of the atmosphere; while Guericke in Germany and Boyle in England discovered other important properties of gases. In dynamics, the direct succession fell to Christian Huygens of Amsterdam, a natural philosopher of very high rank and a worthy successor of Galileo. He completed the theory of the pendulum and by its use determined the acceleration of gravity; invented and constructed the pendulum clock and escapement, discovered the theorems of centrifugal force, and was the first to use what is now called the principle of *vis viva* or kinetic energy. His investigations in optics are also of great importance, and he was one of the first proponents of the wave theory of light.

To try to give in a small fraction of a single chapter any adequate account of the mighty deeds of Newton is, of course, to attempt the impossible. Fortunately the main features of his achievements are so familiarly known that a brief recapitulation is all that is necessary. Born in 1642, the year of Galileo's death, his genius developed with extraordinary rapidity. It appears to be quite certain that the essential parts of all his great discoveries were made before he was twenty-five years old, although most of them were published much later. The

[1] The necessary brevity of this chapter may result in giving the impression that Galileo had no forerunners. This is of course not the case. Archimedes has already been mentioned—a lonely genius who laid firmly the foundations of the statics of solids and liquids. Stevinus, sixteen years older than Galileo, made notable additions to the Archimedean statics. And a century earlier Leonardo da Vinci (a miracle of versatility) had made important discoveries in statics, and had found the true law of the refraction of light. Most of Leonardo's scientific work, however, remained buried in his manuscript notes and has only recently been revealed to the world.

delay was due partly to lack of facilities for publication, but mainly to Newton's carefulness in verification and in working out all possible consequences of his hypotheses. His first great discovery (made in the year in which he received the bachelor's degree at Cambridge) was the "direct and inverse methods of fluxions" which are in all essentials identical with the differential and integral calculus, but with a less convenient and fertile notation. This discovery belongs of course primarily to the history of mathematics; but both physics and astronomy may proudly claim it as belonging partly to them for two reasons; first, because it was the exigencies of their problems which led directly to it; and secondly, because it was an absolutely indispensable tool for the mechanical and astronomical discoveries of Newton and his successors. In the same year (1665) Newton "began to think of gravity extending to the orb of the moon"; he soon found from one of Kepler's laws that the forces which keep the planets in their orbits must vary inversely as the square of their distances from the sun. He applied this rule to the earth and moon and found an approximate agreement between the force necessary to keep the moon in her orbit and the force of gravity at the surface of the earth. "All this," says Newton in later life, "was in the two plague years of 1665 and 1666, for in those days I was in the prime of my age for invention, and minded mathematics and philosophy more than at any time since."

During the twenty-one years which elapsed before the publication of the *Principia* in 1687, Newton, in the midst of other duties and of investigations on other subjects, recurred again and again to the astronomical and dynamical problems which had engaged his youthful attention. It was only after ten or twelve years that he cleared up the difficulties of centrifugal force (Huygens' previous work being then unknown to him) and thus discovered that the two remaining laws of Kepler were consequences of his gravitational law. In the last three

or four years of the period under consideration he appears to have worked steadily at the development of the subject and to have discovered the large number of important theorems and relations which make the *Principia* the most stupendous and overwhelming publication in the history of science.

In all this work there are three streams of discovery which may be separated by logical analysis, but which are so closely intermingled that it is difficult to see how any one of them could have gone on without the other two. Nobody has ever been able to believe that Newton could have extended the Galilean dynamics to the intricate motions of the planets except by the aid of the method of fluxions or its equivalent; and certainly nothing could have been done without a knowledge of the law of gravitation. On the other hand, the solution of astronomical problems required and facilitated a more exact formulation of the principles of mechanics than Galileo had been able to give; although mathematically intricate, they are dynamically simpler than terrestrial problems, since no appreciable frictional or dissipative forces are present; and they furnish tests and verifications of dynamical laws of far greater accuracy than can be obtained in any other way.

Under such conditions it seems futile to attempt to decide whether physics is most indebted to Newton for the formulation of the laws of motion, for the discovery of the law of inverse squares, or for the invention of the fluxional calculus. Any one of the three (if it could have been produced alone) would have made his name immortal; the fact that we owe all three to one person places him upon a pinnacle of greatness which has not even been approached by any other man of science.

I must not neglect to mention also Newton's contributions to optics, which, while not of the fundamental importance of those we have just been discussing, were nevertheless worthy of their author. We need only to recall that he investigated

the composition of white light, the colors of thin films, diffraction, and the possibilities of achromatism in refracting telescopes. He was not infallible; for he decided that it was impossible to make an achromatic refractor, and he supported the corpuscular theory of light against the undulatory theory of Huygens. In both cases, however, the evidence obtainable in his time strongly supported his position; and I think it was this, rather than the mere authority of his name, which caused the corpuscular theory to prevail during the following century.

In the eighteenth century the development of mechanics and of gravitational theory was carried on by the three Bernoullis, Euler, Clairaut, d'Alembert, and others. This development reached its culmination near the end of the century in the publication of Lagrange's *Mécanique Analytique* and of the *Mécanique Céleste* of Laplace—works which for completeness and finish have seldom, if ever, been excelled. The period was not characterized by new discoveries of the first magnitude but by the careful working out of the theories founded by Galileo and Newton and the perfection of mathematical methods for dealing with complicated problems. This was an admirable preparation for the great outburst of discovery which began toward the end of the eighteenth century and was continued still more conspicuously in the first years of the nineteenth.

In other branches of physics and in chemistry, the ground was also being prepared in a different way by the accumulation of experimental facts and relations which formed the raw material for the generalizations of the period which was to come, and served as starting points for notable advances. It is necessary, therefore, to go back and to trace briefly the course of the tributary streams of discovery which were soon to join the main current. We shall have to consider what had been learned about magnetism, electricity, light, and heat.

The ancients were acquainted with the curious property

possessed by the lodestone of Magnesia of attracting iron, and also knew that when amber was rubbed it attracted bits of straw and other light bodies. Nothing came of this knowledge for centuries; but at some unknown time prior to the Crusades, the north-seeking property of the magnetized needle was discovered and the mariner's compass was invented. The science of magnetism was indeed almost the only part of physics that made any progress during the Middle Ages. In the thirteenth century Petrus Peregrinus of Picardy, experimenting with a spherical lodestone and a needle, found that the stone possessed two "poles" which appeared to be the seat of the magnetic power.

The true founder of both magnetic and electric science, however, was William Gilbert of Colchester, physician to Queen Elizabeth. Twenty-four years older than Galileo, Gilbert must be regarded as one of the pioneers of the experimental method. His work had not the scope and depth which characterized that of the great Italian, nor were its consequences so immediate and so revolutionary; but he was nevertheless a truly scientific experimenter and, considering the time in which he lived, we must regard him as a prodigy of originality. He showed quite conclusively that the behavior of the compass was due to the fact that the earth itself was a great magnet. For two thousand years it had been supposed that amber alone was capable of being excited by friction to attract other bodies; Gilbert found that many bodies could be thus excited and that among them were such commonplace substances as glass, sulphur, and resin. His experiments and his reasoning were sound, and he devised a hypothesis of "electric effluvia" which was helpful to electrical science for a long time.

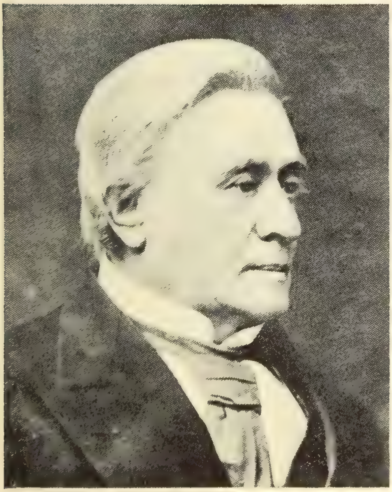
During the eighteenth century the experimental knowledge of both electricity and magnetism progressed rapidly. The conduction of the electrified state by metals was discovered by Stephen Gray; the Leyden jar was invented; de Fay found

that there existed two opposite states of electrification which he called vitreous and resinous and that these behaved, as to attractions and repulsions, like the two poles of a magnet. America made her first contribution to physics in the very important work of Benjamin Franklin. Toward the close of this period of activity the doctrines of electric effluvia and of Cartesian vortices had been definitely replaced by the theory that the forces observed were due to action at a distance between charges of a single electric fluid and matter (Franklin) or to a similar action between two fluids (Coulomb). Eventually the law of variation of this force with the distance was experimentally determined by Coulomb and found to be the familiar inverse square relation of Newton. The same law was shown by Coulomb to hold for the forces between magnetic poles also; and either one, or two, magnetic fluids had to be predicated to account for the variation in the strength of magnets. Indeed, the application of gravitational theory to these forces rendered inevitable the introduction of such imponderable fluids to take the place of the material masses which play the same rôle in the case of gravitation.

I have already mentioned briefly Newton's researches in optics and his adherence to the corpuscular theory in which he was followed by most philosophers. This introduced another "imponderable" which was, however, supposed to consist of excessively minute discrete corpuscles instead of a continuous fluid. Many important optical phenomena had been discovered. Descartes had published the mathematical law of refraction, which, however, was not his own discovery but was apparently communicated to him by Snell of Leyden; Newton had discovered and properly interpreted the composite nature of white light and had investigated the simpler cases of diffraction and of what is now called interference; Huygens had observed double refraction in Iceland spar and had given the proximate explanation of it (on the wave theory) which is still current;

Alessandra Volta.

André Marie Ampère.



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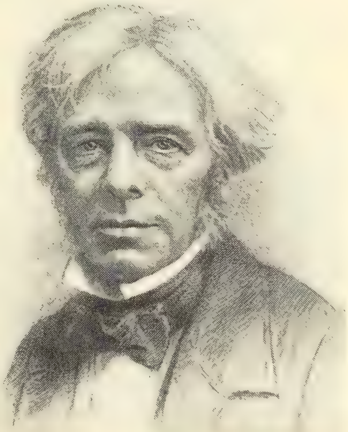


Michael Faraday.

and he observed that the two beams which had passed through the spar differed from each other and from ordinary light in the peculiar way which we now indicate by calling them polarized. Space is lacking for any discussion of the ingenious arguments by which the two rival theories of light were supported.

The quantitative study of heat begins with Galileo's construction of the first thermometer—an air-thermometer of considerable sensitiveness but of inconvenient design. Improvements of one kind or another were made by many men and the fixity of certain temperatures (such as that of melting ice) was established. The first really reliable thermometers were made by Fahrenheit in the first quarter of the eighteenth century. All of the early thermal experiments and theories were confused by the failure to distinguish clearly between temperature and quantity of heat, and by the great and apparently capricious differences between the heat capacities, or specific heats, of different substances. All these difficulties were finally cleared up in a masterly manner by Joseph Black near the end of the period we are considering. He established calorimetric measurements on a firm basis, and showed quite clearly that in all such experiments heat behaves like a substance which passes from one body to another and sometimes becomes "latent" for a time (as when ice melts) but which is never created or destroyed. All these conclusions are true within the range of Black's experiments; and it was only at a later date that the exceptions were seen to be of great importance and not explicable by appealing to latency or to a variation in heat capacity. What was known at that time thoroughly justified a substantial theory of heat as the most convenient hypothesis available; and thus another imponderable fluid took its place as a respectable and useful article in the physicist's creed. Many unavailing attempts were made to show the identity of two or more of these hypothetical substances. Thus, on account of the phenomena of radiant heat, it was proposed to

identify caloric with the light corpuscles; but the fact that light passed through glass while radiant heat did not, was an insuperable obstacle to this view. There was always in the background the possibility that both heat and light were forms of motion, but at the period now under consideration the substantial theories undoubtedly held the field. This state of things led to very sharp boundaries between the different fields of physics and discouraged the natural inclination to apply the principles of dynamics (which by this time had come to seem almost intuitive) to other physical phenomena. There was no great encouragement to apply the principles of mechanics to the imponderables; so far as experiment showed they lacked not only the conspicuous property of weight but also the most essential dynamical characteristic of ordinary matter, inertia. The natural and fertile method of dealing with them was to take as postulates for the mathematical development of the subject certain empirical relations as simple and fundamental as possible. It was not until the establishment of the conservation of energy in the late forties of the nineteenth century that the barriers between the different "physical forces" were broken down.

The intervening period, however, was one of brilliant discovery in both mathematical and experimental physics. In the theory of heat two works of this period must at least be mentioned. In 1822 Joseph Fourier published his *Théorie Analytique de la Chaleur,* a work of genius which has had a profound effect in almost all branches of theoretical physics and upon pure mathematics as well. A still more momentous event in the history of science was the publication in 1824 of Carnot's *Réflections sur le Puissance Motrice du Feu.* His primary purpose was the investigation of the efficiency of heat engines, which had recently become a matter of interest owing to the increasing use of the steam engine invented by Newcomen and Watt. In this paper Carnot makes use of an analogy; he saw

that the production of work by an engine might be regarded as due to the fall of caloric from a higher to a lower temperature, just as the work of a water mill is a consequence of the fall of water from a higher to a lower level. He follows a course of reasoning so simple yet so effective that it seems inspired; it is based upon the denial of the possibility of perpetual motion, which even at that time was a pretty firmly established empirical fact, owing to the consistent failure of all attempts to produce such motion. He thus establishes the general principle which is now called "the second law of thermodynamics" and which is of far wider application than could have been imagined by Carnot or any of his contemporaries. For it happens that nearly every phenomenon in the physical universe is attended by an evolution or absorption of heat and is therefore subject to the second law. It governs every chemical reaction, as was shown by Willard Gibbs fifty years later, and the physical and chemical processes of life. It sets bounds to cosmological speculations and to forecasts of the future of the human race. Not the slightest deviation from it has ever been observed and the probability of such deviation is so minute that it must be regarded as one of the most firmly established of scientific facts.

In electrostatics and magnetism this period was marked by the development of the mathematical consequences of Coulomb's discovery that the inverse square law applies to these forces. Much of the gravitational theory could be taken over directly, while special applications to electricity were made by Poisson, Green, and others. In the meanwhile, however, another set of electrical phenomena had appeared. In 1791 Galvani, professor of anatomy at Bologna, gave an account of his experiments on the contraction of frogs' legs when touched with two different metals in series and, with much ability, supported the view that it was an electrical manifestation. He naturally supposed that the origin of the electrical

disturbance was in the animal tissues. This was combated a year later by Volta, who referred the seat of the forces involved to the point of contact between the dissimilar metals, and gave good evidence that they were electrical. The effects, however, were very small, and interest flagged until 1800, when Volta invented the "pile," by means of which very appreciable results could be obtained. This at once excited much attention; and in the same year Nicholson and Carlisle in England in experimenting with the Voltaic pile observed the decomposition of water by electrolysis, and shortly afterward Humphry Davy advanced the chemical theory of the pile, which, after many years of struggle, eventually superseded the contact theory of Volta. There was a rapid advance in the knowledge of the electric current, of batteries, and of the electrolytic process. These experiments produced a profound effect upon chemistry through the electrochemical theory of Berzelius; and although this has long been given up, the most modern theories have, in a different form, reverted to the view that chemical forces are of electrical origin.

Many attempts had been made to discover some connection between the phenomena of electricity and those of magnetism, but all had failed until 1820, when Oersted of Copenhagen observed and correctly described the action of an electric current upon a magnet brought near it. As soon as the news of this observation reached Paris, Ampère began the series of investigations which was to render his name immortal in electrical science. Within a week he had demonstrated to the Academy the attractions and repulsions of parallel currents; and during the ensuing three years his brilliant experimental and mathematical researches laid a sure and firm foundation for all the subsequent developments in electrodynamics. As was to be expected, he based his investigations on the Newtonian model, by using current-elements acting upon each other by forces in the line joining them. Again the law proved to be

that of the inverse square; but the fact that the attracting elements were directed quantities added many difficulties, which, in the state of mathematical science at that time, gave ample scope to the "Newton of electricity" for the display of his genius. The vector relations involved in the statement of his problem caused an indeterminateness which later gave rise to many rivals to Ampère's expression for the force between current elements. These all gave the same result when integrated around closed circuits which alone were amenable to experiment; and no one could succeed in devising experiments which would discriminate between them. One of these rival theories, that of Weber, is interesting as being in some respects similar to the modern theory of electrons.

Great as is the debt which electrical science owes to Ampère, it is exceeded by its obligation to Faraday whose marvelous experimental skill and instinctive perception of the inner nature of phenomena are still the wonder and admiration of all men of science. At twenty-one years of age he was a journeyman bookbinder, who had educated himself in some degree by reading the books which he was given to bind. The *Encyclopædia Britannica* aroused his interest in science and he applied to Davy for employment in the Royal Institution. For a number of years, as Davy's assistant, his chief work was in chemistry; but Oersted's discovery turned his thoughts toward electricity and thereafter it was his principal field of work. In 1831 he made the capital discovery of the induction of currents, which is not only of the most fundamental consequence to the theory of electromagnetism but is the foundation of the innumerable practical applications of electricity to the uses of man. Of his many other discoveries I shall mention only two: the quantitative laws of electrolysis which bear his name and which gave the first suggestions of an atomic theory of electricity, and the specific inductive capacity of dielectrics.

Because of the deficiencies of his early education, Faraday

never acquired the technique of the mathematician. But, as Maxwell has pointed out, his mind was admirably fitted for dealing with quantitative relations. He overcame the handicap under which he suffered by devising his own methods of representing the quantitative side of phenomena—methods which not only enabled him to achieve his unparalleled success as a discoverer but which are so useful to others that they have held the field in elementary instruction in electromagnetism as well as in the most complicated problems of modern electrical engineering. His lines of force were to him real entities and he conceived of all forces as being transmitted from point to point in a continuous medium. The idea of action at a distance was repugnant to him. It is indeed to most physicists, but Faraday was not tempted, as most of us are, to use distance forces because of their mathematical convenience and thus to escape the prodigious difficulties of imagining a medium with the necessary properties to account for the forces. Faraday's prejudices were to have important consequences in the next generation, as we shall see when we come to speak of Maxwell.

The year 1800 is an important date in the history of optics, as it is in that of electricity; for in that year Thomas Young took up the cudgels for the wave theory of light which had been almost completely neglected since the time of Huygens. In the following year he explained the colors of thin films (Newton's rings) by means of the "interference" of waves; and in 1803 he applied the same idea to certain problems of diffraction, but in a way which was afterward proved to be wrong. He was drawn into a controversy with the great Laplace, who had worked out a theory of double refraction on the corpuscular basis; and for a dozen years or more Young found little sympathy and support for his views among scientific men of established reputation. Indeed, he was far from having a good case; the explanation of diffraction was not satisfactory; there was no explanation of polarization, since

waves in the tenuous and fluid ether were quite naturally supposed to be compressional like sound waves in air; and, for the same reason, no satisfactory explanation of double refraction appeared to be possible.

The first defect was remedied by the work of Fresnel, presented to the Paris Academy in 1816, in which the author began that brilliant series of experimental and mathematical investigations which left the wave theory completely victorious over its rival. He gave the true theory of diffraction by a slit and a wire and showed that it agreed with the results of his experimental measurements. Poisson, who was one of the referees of his paper, noted the serious objection that Fresnel's theory would require a bright spot in the exact center of the shadow of a circular object. When, however, the matter was put to the test of experiment under suitable conditions, the bright spot was found and this naturally produced a reaction in favor of Fresnel's theory. It appears to have been Young who took the bold step of suggesting that the vibrations in light waves were transverse and that thus polarization could be explained. Fresnel at once took up this suggestion and succeeded in bringing into line all the intricacies of crystalline refraction, including that in biaxial crystals which had been discovered a few years before by Brewster and had been a stumbling-block to all other theories. Later he took up the theory of reflection and refraction by ordinary transparent bodies with equal success; and since the completion of his series of memoirs there has never been a doubt in the mind of any competent person that light has the kinematical properties of transverse wave motion.

On the dynamical side, however, matters were not so clear. Only a solid can transmit transverse elastic waves and it was difficult to believe that the ether could be a solid and yet allow the free motion of material bodies through it without the slightest detectable resistance. This was the origin of the

great problem of the existence and properties of the ether—a problem which has excited the most eager interest of physicists for a hundred years and is still with us. Many of the most important discoveries, mathematical and experimental, have arisen from attempts at its solution. It at once stimulated the mathematical study of the theory of elastic solids and of the applicability of this theory to the phenomena of light. The work of Cauchy, Green, McCullagh, Stokes, and Kelvin in this field may be said to have created a new era in mathematical physics and even in mathematics itself; for the treatment of continuous media required methods which differed in many ways from those appropriate to distance forces of the Newtonian type. It was also the first attempt to apply in all strictness the principles of dynamics to natural phenomena outside the restricted field of mechanics proper. It was never perfectly successful, but so nearly so that there was constant encouragement to persevere. We shall have occasion to look at a second phase of this gallant attack upon the mysteries of nature when we come to deal with the work of Clerk Maxwell.

About the middle of the century occurred the epoch-making discovery of the conservation of energy, which brought all kinds of physical and chemical phenomena into much more intimate relation with each other than had previously been suspected. Incidentally, it greatly strengthened the tendency, of which I have just spoken, to seek for a strictly dynamical foundation for all such phenomena.

The discovery arose primarily in a reconsideration of the nature of heat, and its history is so curious and interesting that it is with regret that I recognize the impossibility of giving an adequate account of it within the limits of this chapter. As we have seen, the belief that heat was a substantial fluid had prevailed for many years and had proved useful; but there had always been a suspicion (extending back to the time of Hooke and Newton) that it might be an effect of motion—either of

Hermann von Helmholtz.

Lord Kelvin.

Heinrich Rudolph Hertz.

James Clerk Maxwell.

the fine particles of which ordinary matter was made up, or of light-corpuscles within matter. At the end of the eighteenth century, Count Rumford had made experiments which ought to have started things in the right direction, but were disregarded. Carnot himself, in some posthumous notes which were not published until 1878, gave so clear an outline of the true theory that we cannot doubt that the course of science would have been greatly altered, as Mach remarks, if Carnot had not died of cholera in 1832. The caloric theory was finally overthrown by the labors of two men, Mayer and Joule, quite independently and neither having in the beginning any knowledge of the work of the other. Mayer, a Jewish physician of Heilbronn, began his process of reasoning with the observation that venous blood is a brighter red in tropical than in temperate climates. He was so ignorant of the terminology of physics that he could not make himself understood at first and suffered many rebuffs in consequence. His persistence, however, was sublime; he learned to write so that physicists could understand him, unearthed forgotten experiments, and eventually, without any experiments of his own, gave conclusive evidence for his theory and obtained a good value of the mechanical equivalent of heat. There could scarcely be a greater contrast than that between him and his fellow discoverer. Joule was a Manchester brewer and amateur of science, a skillful and accurate experimenter who year after year turned out unimpeachable quantitative evidence of the equivalence between mechanical work and heat in all sorts of transformations. A third collaborator in placing the new theory on a firm foundation was Helmholtz, whose celebrated memoir of 1847 showed clearly the generality of the new principle and its applicability to all branches of science; he gave it suitable mathematical formulation and demonstrated its great power in finding relations between phenomena of apparently different kinds.

The next step was the reconciliation of the new principle

with that of Carnot, and it proved to be a difficult one. It puzzled Kelvin for several years and delayed his complete adherence to Joule's theory; ultimately he saw his way clearly, and as a result of his work and that of Clausius the modern theory was established upon the two principles which stand side by side as the first and second laws of thermodynamics. These two empirical principles are probably the most firmly established and most thoroughly verified of all the so-called laws of nature. In the classical treatment of the subject they are regarded as axioms and deductions are made from them, so that, in form, the science is like geometry. As I have previously intimated, the results obtained are of great generality and of far-reaching consequence in practical applications as well as in philosophical implications. It is one of the great triumphs of theoretical physics.

Side by side with this theory there grew up another method of dealing with the subject which was less general and more hypothetical, but has proved to be an invaluable aid to research. As soon as it was recognized that heat and mechanical energy are mutually convertible, it became inevitable that physicists should seek for a detailed mechanical theory of heat. The obvious hypothesis was that heat consisted of the energy of motion of the small particles, or molecules, of matter, whose existence had been more or less generally accepted since Dalton's introduction of the atomic theory to account for the chemical laws of definite and multiple proportion. In order to develop this theory, the laws of mechanics had to be applied statistically to enormous aggregates of molecules reacting upon each other in various ways. The simplest state of matter from this point of view is the gaseous one; and in the hands of Clausius and Maxwell the kinetic theory of gases made great progress in a few years. Atomic and molecular theory became at once definite and quantitative. One of Dalton's atoms might be of any size, so long as it was small enough

to escape individual observation and had the correct ratio of mass to other atoms; but the atoms and molecules of the physical theory had definite and calculable mass, size, velocity, and free-path. They became very real to physicists and were constantly used in reasoning and in planning experiments.

About twenty-five years ago a determined attack upon all atomic theories was made by Ostwald and his followers among the physical chemists—largely through ignorance of the real evidence upon which they were based. They ridiculed such theories as metaphysical figments of the imagination and attacked them as obstacles to real advance in the philosophy of nature. The faith of physicists, however, was not for a moment shaken; and it has been justified by the progress of discovery in the intervening years. The last doubting Thomas has been convinced and only those who deny the objectivity of matter itself can now question the real, physical existence of atoms and molecules.

Through the labors of Boltzmann, Gibbs, and others, the application of statistical mechanics to molecular problems was developed and generalized so as to be applicable to other states of matter than the gaseous one; and attempts were made to reduce the whole of thermodynamics to a mechanical basis. The subject is a very difficult one with many pitfalls for even the most wary; and we must conclude, I think, that the attempt has met with a defeat that is probably final. It has, however, led directly to the quantum theory of Planck, a great generalization which is the most puzzling and the most promising treasure in the possession of the physicist of today.

The next great landmark of which we must take note is the unification of the theories of electrodynamics and of optics by Clerk Maxwell. He himself tells us that, impressed by the value and fertility of Faraday's ideas, he decided, in beginning his serious study of electricity, to read no mathematics on the subject until he had mastered Faraday's *Experimental Re-*

searches. Maxwell was a highly trained and original mathematician, and his first papers on electrodynamics were devoted to the expression in clear mathematical form of some of Faraday's hypotheses and modes of thought. Like his chosen master, he rejected action at a distance and concentrated his attention upon the hypothetical medium by means of which electromagnetic forces might be transmitted. In several memoirs published during the sixties he gave details of mechanical models which were adapted to this end. By gradual steps these auxiliaries were done away with and at the same time the theory far outgrew its original purpose of translating Faraday into mathematical language. Maxwell showed clearly that all the known facts of electrodynamics could be attributed to the action of a medium, and by strict mathematical reasoning he deduced the properties which this medium must have. These turned out to be identical in all details with those which we must attribute to the luminiferous ether in order to account for the phenomena of light. Thus was born the electromagnetic theory of light and two great domains of physics were brought together under a single system of hypotheses clearly expressed in the form of differential equations.

The publication of Maxwell's *Treatise on Electricity and Magnetism* in 1873 was an event of the first importance in the history of science. The new theory was slow in making its way, especially on the continent of Europe, and Maxwell himself died in 1879. His work was taken up, however, by a group of devoted adherents, among whom we may mention Heaviside, Lodge, Rowland, Poynting, Gibbs, J. J. Thomson, and Larmor. In 1886 Hertz, whose attention had some years before been directed to Maxwell's theory by Helmholtz, made an accidental observation which to his acute mind offered the possibility of a direct test of the finite speed of propagation of electromagnetic action. His brilliant series of experiments demonstrated the existence, speed, and properties of electro-

magnetic waves and served as a complete verification of Maxwell's theory. It is well known that the wonders of wireless are a direct consequence of the experiments of Hertz; but to the physicist this is less interesting and significant than the steady growth in scope and authority of Maxwell's equations, which come nearer to the ideal of a "world formula" than anything else known to the modern man of science.

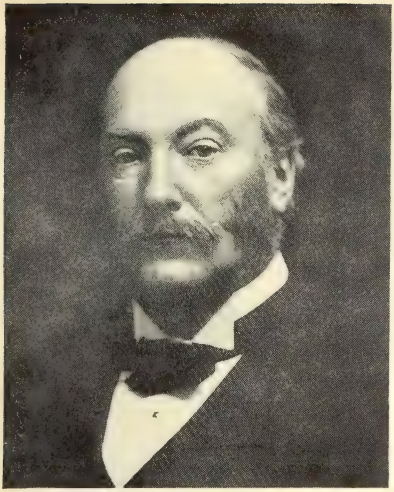
For something like ten years it was generally supposed that the main outlines of the science of physics had been drawn in fairly satisfactory, and perhaps final, form. There was still much to be done, but it would be concerned with details—with perfecting theories and increasing the accuracy of measurements. A great deal of very valuable work of this kind was done in many fields; as an example I may refer briefly to the development of accurate measurement in spectroscopy.

The use of the spectroscope as a method of chemical analysis was placed on a sound basis about 1860, by Bunsen and Kirchhoff, and the application of this method was extended, by the brilliant discovery of Kirchhoff, to the atmospheres of the sun and stars. Everyone knows something of the wonderful results which have followed the application of the spectroscope to astronomical problems and of the growth of the borderland science which is called astrophysics. Great improvements in spectroscopic apparatus were made by Rowland, Michelson, and others, and there grew up a body of skillful spectroscopists, who devoted themselves to the accurate measurement of the wave lengths of the innumerable spectral lines given out by the different chemical elements and to the discovery of empirical relations between the numerical values of these wave lengths. It was hoped that such observations would throw light upon the structure of atoms, but for many years no progress was made in this direction. Indeed, it is only recently that the results of a generation of spectroscopists are beginning to be useful for this purpose and only after the clue to a theory

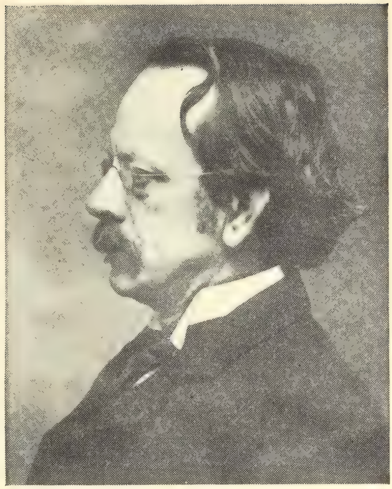
of atomic structure had been given by investigations in other fields. Spectroscopy is almost the only part of physics in which a large mass of data was accumulated before the existence of a guiding hypothesis or theory to direct the work. The method of simple induction and classification which has played so large a part in some other sciences seems to be unsuited to the problems of physics.

Accurate measurements, however, do sometimes produce brilliant discoveries—when they fall into the right hands. A classical example of this is the discovery of argon by Lord Rayleigh, as the result of a quite prosaic undertaking to redetermine with great accuracy the density of nitrogen. As a sequel to Rayleigh's work, a whole family of chemical elements, whose existence had been entirely unsuspected by chemists, was discovered by Ramsay. But it is only in rare instances that this sort of thing occurs; usually an accurate measurement leads to no exciting result, but takes its place among the solid foundation stones of the science. And for perhaps a decade there was fairly widespread opinion among physicists that this was what they must look forward to, and that the future of physics lay "in the last place of decimals."

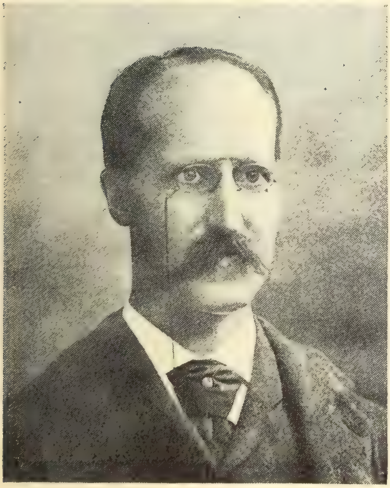
These anticipations of a useful, if somewhat dull, old age for the science were happily disappointed in the last years of the century by the remarkable outburst of unexpected discoveries, among which the Röntgen rays came first in point of time. This was followed almost at once by Becquerel's discovery of radioactivity, the identification of the subatomic "corpuscle" or electron by J. J. Thomson, and the investigations of the ionization of gases which have led to many important results. No physicist who has reached middle age can forget the romantic interest of the ten years following 1895, when startling discoveries followed each other in rapid succession and the physical journals were awaited with an impatience not unlike the desire for newspapers in wartime. But



Lord Rayleigh.



Sir Joseph John Thomson.



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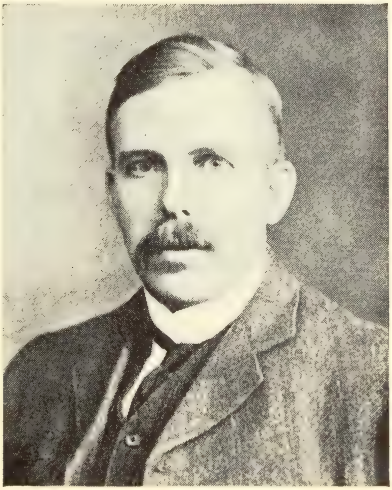


Sir Ernest Rutherford.

the news was all good news, and recorded an almost unbroken series of victories.

These discoveries were, as I have said, unexpected, but they were not in any real sense accidental. They came as the result of a careful and prolonged study of the electrical discharge through rarefied gases—a complicated set of phenomena very difficult to put in order. Twenty years earlier, Maxwell had predicted that the next great step in our knowledge of the relations between electricity and matter would come from a study of the discharge through gases; and it had been prosecuted in that spirit by many men, though the clue which they sought eluded them for twenty years. When it did come at last, it was in a form which was, so far as I know, entirely unpredicted and unexpected. This was so much the case that it took us more than fifteen years to find out quite certainly just what the X-rays were. It was not until 1912 that Laue's discovery of the diffraction of X-rays by crystals and the subsequent work of W. H. and W. L. Bragg made it quite certain that these rays were of the same nature as light but with wave lengths only about $\frac{1}{5000}$ of those in the visible spectrum. This had indeed been for some time the prevailing hypothesis as to their nature, but there was little quantitative evidence to support it; and only a year or two previous to the discovery of crystalline diffraction W. H. Bragg himself had brought forward many reasons for thinking that X-rays might be corpuscular. The study of these very short waves has already given us invaluable knowledge of the nature of the atoms or different elements and promises still greater advances in the future; it has provided a new and powerful method of studying crystal structure and has revolutionized our conception of the nature of chemical combination in crystalline bodies; and it promises to have practical applications as useful in industry as ordinary spectroscopy.

The discovery of radioactivity by Becquerel followed al-

most immediately upon Röntgen's discovery of X-rays, and was in a sense a direct consequence of it; they are alike, too, in that they have both had important medical applications which have drawn much public attention. Madame Curie's sensational discovery of radium was an early incident in the history of this subject. But by far the most important development in this field was the establishment by Rutherford and his pupils of the cause and source of energy of these radiations. He has shown in the most conclusive way that they are due to the disintegration of the atoms of the radioactive elements—uranium, thorium, radium, etc.—and that a spontaneous transmutation of these elements is going on constantly. The genealogy of the radioactive elements is known more accurately than that of most royal families; and the birth and mortality statistics of the various kinds of atoms are in all the textbooks. Thus a part of the dream of the alchemists has come true, but only a part; for up to the present all attempts to produce artificially the transmutation of the heavy elements have failed. In fact, we have not been able to affect in the slightest way the spontaneous transmutation of the radioactive elements; it can neither be retarded nor accelerated by any agency at our command. We do know, however, that vast stores of energy are locked up in the atoms of the heavier elements, and if the time should ever come when this can be released and controlled by man it will doubtless cause a revolution in industrial processes more fundamental than that which followed upon the introduction of steam and electricity. One small step in this direction has been taken within the past few years. Rutherford has obtained evidence that the nitrogen atom may be broken up by bombardment with alpha rays, and that one of the products of this process is hydrogen. It is perhaps too early to regard this as being definitely established; and, even if it be true, the amount of matter transmuted in this way is excessively minute, while the quantity of energy released in the process

(if any) is far below what could possibly be measured experimentally. We have, however, become accustomed to small beginnings which ultimately produce great results; and a modern physicist would be rash indeed who should attempt to set bounds to the possibilities of future discovery in this direction.

The discovery of the electron was also an event of the first importance in the history of our science. It is the ultimate atom of negative electricity and is a constituent of all material atoms. It can also exist in the free or "disembodied" state, as, for example, in the cathode rays, the beta rays from radium, and in the electronic stream from incandescent bodies. In the last of these forms it has proved to be of great practical use to telephony and wireless telegraphy in the audion or thermionic tube which is the cause of most of the remarkable advances in these fields during the past five or six years. To the physicist and chemist of today the electron is an indispensable concept in both theoretical and experimental investigations; and its reality can be questioned only on those philosophical grounds which may put in doubt the existence of matter itself.

The nature of positive electricity is not so definitely known; but evidence is accumulating that it too exists in an atomic form as the "nucleus" of the atom of hydrogen—the residue left when the hydrogen atom is deprived of its single negative electron. It is becoming probable that the "nuclei" of other atoms are built up out of these and of negative electrons. If this group of hypotheses should stand the test of time we shall have to conclude that matter and electricity are different aspects of the same stuff—that the atoms of matter are formed by different collocations of the atoms of positive and negative electricity.

Another line of physical inquiry which has proved to be of deep and fundamental significance is the so-called quantum theory of Planck. It originated in the study (both experimental and theoretical) of the intensity and quality of the

radiation from a "black body," or perfect radiator, when held at a definite temperature. The total intensity of such radiations were deduced theoretically by Stefan from the principles of thermodynamics and the predicted results have been amply verified by experiment. When, however, the attempt is made to predict the way in which the energy is distributed in the spectrum, so as to be able to tell what fraction of the total intensity is carried by any particular wave length, the problem becomes much more difficult. It is necessary to have recourse to statistical methods analogous to those used by Maxwell, Boltzmann, and Gibbs in accounting for the thermodynamic properties of material bodies. First steps in this direction were taken by W. Wien, but the deductions from his theory were not altogether in accord with experimental results. Planck succeeded in obtaining a formula which agreed with experiment, but only by making certain very daring hypotheses; the most conspicuous of these is that the emission or the absorption of radiation, or both, takes place not steadily and continuously, as we had always supposed, but by finite, discrete "quanta." From one point of view this hypothesis of Planck may be regarded as extending the field of the atomic theory, hitherto restricted to matter, to energy as well. I cannot hope to suggest even remotely in the brief space at my disposal how revolutionary Planck's assumptions really are; they are still very imperfectly understood and it has not yet been possible to reconcile them wholly with other facts and general laws which appear to rest upon very solid foundations. Indeed, if the results of Planck's speculations had been confined to the deduction of a formula for the radiation of a black body, they would not, I think, have long engaged the serious attention of physicists. But they began to turn up unmistakably in many other fields of investigation—for example, in connection with the photo-electric effect, with X-rays, and in all theories of atomic structure. At present no one doubts that most of our

fundamental ideas in mechanics and electrodynamics must be revised in the light of the quantum theory, which, however, is itself still in a very immature state. The problem thus arising of bringing together under one system apparently discrepant bodies of phenomena is an exceedingly difficult one, and we may have to wait for another Newton to solve it. But it possesses the greatest fascination for all theoretical physicists; they are able to congratulate themselves upon the possession of an unsolved problem of the first magnitude and of great difficulty and they know that as long as it lasts, life will not be dull for them.

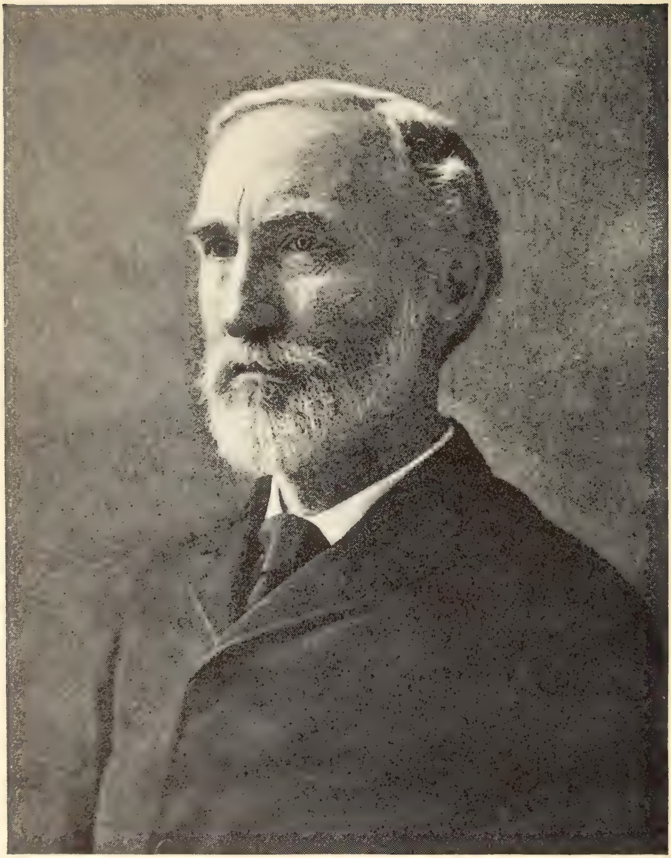
I should be in despair if it were necessary to give, at the end of a chapter already too long, an account of Einstein, relativity, and gravitation. Fortunately any need that you may feel for instruction on these subjects has doubtless been satisfied by the newspapers, the magazines, and by innumerable books, popular and otherwise. Let me say in all seriousness, however, that the more one knows of the history and recent developments of physics the more sincere and ardent is one's admiration for the individuality and brilliant originality of Einstein's genius. It does not seem probable at present that his discoveries will have as great an effect upon the immediate future of physics as some of the others which I have just discussed. But the ultimate result of his work upon *methods* used in the theoretical side of physical science may well prove to be revolutionary; and it seems highly probable that it will change to some extent our philosophical views of the nature of the external world and of our relation to it.

It may appear that, in my hurried sketch of the progress of physics since 1895, I have made very frequent use of such terms as "important," "epoch-making," or "revolutionary." The truth is that all the various discoveries and theories which arose more or less independently and have been separately mentioned are constituent parts of one "revolution" which

has not yet reached its climax. It is one of the greatest intellectual pleasures of the present-day physicist to see how all these apparently diverse things are fitting into each other and taking their appropriate places in a general scheme which is rapidly assuming form and coherence. The new ideas in physics are having a profound influence upon the fundamental theories of chemistry and are bringing the philosophies of the two sciences much closer together. They have already made possible a rational theory of the periodic law of Mendeléeff, and have displaced the atomic weight as the controlling factor in the determination of the chemical properties of the elements. They have also given grounds for a very reasonable hope that the near future may see the development of a real theory of chemical combination, which is certainly much to be desired.

The general character of the profound change which is taking place in the fundamental ideas of both sciences may perhaps be stated briefly and inadequately in the following terms. The recent discoveries in physics have enabled us to experiment in several ways with the individual atom and to find out something of its properties and activities. Until recently we have been able to deal only with statistical averages of the behavior of vast numbers of atoms and molecules, and all of our physical laws have been based upon such statistical knowledge. The apparent discrepancies between the older and the newer formulations may well be due to this difference. It is possible that the ultimate laws which govern the actions of atoms are quite different from the laws of mechanics and electrodynamics which are so familiar that they seem almost axiomatic. If this should be so, the well-known "laws" will in no way lose their validity within the field that they have ruled so long; but we shall know that they are not fundamental and primary, but secondary, statistical laws in which much of the individuality of physical activities has been ironed out by the

process of averaging. To come to this point of view is of course rather a wrench for those of us who have been nursed and reared in the old régime. But this discomfort is much more than compensated for by the fascinating and apparently inexhaustible field for research and speculation which is now being opened up for our use and pleasure.



JOSIAH WILLARD GIBBS

CHAPTER III
CHEMISTRY

By JOHN JOHNSTON

PROFESSOR OF CHEMISTRY, YALE UNIVERSITY

CHEMISTRY is the science of the ultimate composition and constitution of matter, of the mutual reaction between two or more substances, and of the influence of factors such as change of temperature, pressure, or extent of surface upon the stability of a substance and its relation to other substances. The chemist studies the great diversity of substances, organic and inorganic, which we see around us; he analyzes these substances, ascertains their composition, and builds them up again from their components; he investigates their behavior with respect to change in external conditions and in relation to other substances. He learns how, not merely to imitate a substance occurring naturally, but to make the identical material artificially and to discover new substances superior in usefulness to those found in nature; and he considers how useful substances may be produced more economically from the raw materials available. The study of chemistry is slowly yielding information as to the nature of biological processes of importance to everyone and so is assisting to retain health and to control disease. Indeed, our material well-being and comfort depend in large part upon a fundamental knowledge of chemical processes and how to control them; and continued progress along these lines will be limited only by the rate at which we extend our knowledge of fundamentals, what chemistry has achieved being but a fraction of what it may do for us.

The great practical achievements of chemistry are comparatively recent, almost entirely within the last sixty years, quite largely indeed within the present century. They are so manifold that it would not be feasible in the space allotted even to mention a fraction of them; consequently I have endeavored only to sketch in general outline, as free from technicalities as possible, the development of the main fundamental principles of chemistry, and even in this have been forced to omit much that is important.

Development of the Idea of Chemical Elements and of Their Mutual Relationship

Two hundred years ago, at which time the classical mathematics had already reached a high state of development, chemistry had not begun to be a science, nor even an art; it was more or less of a mystery, in which language was used to conceal the fact that there was no thought. Boyle in *The Sceptical Chymist,* first published in 1661, refers to the vagueness of the ideas then current in the following terms:[1]

> The confidence wherewith chymists are wont to call each of the substances we speak of by the name of sulphur or mercury, or the other of the hypostatical principles, and the intolerable ambiguity they allow themselves in their writings and expressions, makes it necessary for me . . . to complain of the unreasonable liberty they give themselves of playing with names at pleasure. . . . I cannot but take notice, that the descriptions they give us of that principle or ingredient of mixt bodies, are so intricate, that even those that have endeavored to polish and illustrate the notions of the chymists, are fain to confess that they know not what to make of it either by ingenuous acknowledgments, or descriptions that are not intelligible. . . . Chymists write thus darkly, not because they think their notions too precious to be explained, but because they fear that if they were explained, men would discern, that they are far from being precious. And, indeed, I fear that the chief reason why

[1] The Sceptical Chymist, Everyman's Edition, pp. 113-116.

chymists have written so obscurely of their three principles, may be, that not having clear and distinct notions of them themselves, they cannot write otherwise than confusedly of what they but confusedly apprehend; not to say that divers of them, being conscious to the invalidity of their doctrine, might well enough discerne that they could scarce keep themselves from being confuted, but by keeping themselves from being clearly understood. . . . If judicious men skilled in chymical affairs shall agree to write clearly and plainly of them, and thereby keep men from being stunned, as it were, or imposed upon by dark and empty words; 'tis to be hoped that these men finding that they can no longer write impertinently and absurdly, without being laughed at for doing so, will be reduced either to write nothing, or books that may teach us something, and not rob men, as formerly, of invaluable time; and so ceasing to trouble the world with riddles or impertinencies, we shall either by their books receive an advantage, or by their silence escape an inconvenience.

And again,[2] showing that he had no great opinion of their methods:

Methinks the chymists, in their searches after truth, are not unlike the navigators of Solomon's Tarshish fleet, who brought home from their long and tedious voyages, not only gold, and silver, and ivory, but apes and peacocks too; for so the writings of several (for I say not, all) of your hermetick philosophers present us, together with divers substantial and noble experiments, theories, which either like peacocks' feathers make a great show, but are neither solid nor useful; or else like apes, if they have some appearance of being rational, are blemished with some absurdity or other, that when they are attentively considered, make them appear ridiculous.

The general belief of the alchemists appears to have been that there is a primordial matter which, when combined with more or less of one or more of their four so-called elements or principles—fire, air, earth, and water—becomes apparent to our senses as the various substances we know; in other

[2] *Op. cit.*, p. 227.

words, that matter is the carrier or embodiment of certain qualities which can by appropriate treatment be enhanced or attenuated. It is juster to look upon the alchemists' so-called elements as qualities—such as hotness, coldness, dryness, wetness—typified by the things named, though no single quality would suffice for a single element, as each alchemist tended to endow his elements with such attributes as suited his immediate purpose. In addition to these four elements some made use also of the "hypostatical" (fundamental) principles—salt, sulphur, and mercury, which again may be interpreted as typifying fixity in the fire or incombustibility, combustibility, volatility, and metallic luster, respectively. Such views lead one directly to believe in the possibility of transmutation, of changing base metal into gold; for to achieve this, it would be necessary only to effect a suitable change in the proportions of the elemental qualities, a possibility which therefore seemed far from hopeless or absurd.

It is clear that no great progress in chemistry as a science could have been made, so long as such false views prevailed. And indeed the alchemists contributed nothing to the real philosophy of chemistry, although they did discover—by chance, more or less—a number of useful substances, such as sulphuric acid (oil of vitriol) and tartar emetic, some of which found application as drugs. For one of the tasks they set themselves was to find the elixir of youth, a quest along with which went a belief in the efficacy of doses of the strangest mixtures; indeed, an ingenuous person examining the present-day official pharmacopœias might well be led to think that the alchemists continued to flourish and to be powerful until very recent times.

The overthrow of this false philosophy was begun by Robert Boyle, in his *Sceptical Chymist.* He endeavored to distinguish the qualities of a substance from its composition, and enunciated views with reference to the difference between elements and compounds which are still held. Thus he writes: "I must

not look upon any body as a true principle or element, but as yet compounded, which is not perfectly homogeneous, but is further resoluble into any number of distinct substances, how small soever." "I mean by elements, as those chymists that speak plainest do by their principles, certain primitive and simple, or perfectly unmingled bodies; which not being made of any other bodies, or of one another, are the ingredients of which all those called perfectly mixt bodies are immediately compounded, and into which they are ultimately resolved."[3]

It is difficult to picture the exact status of knowledge of chemical art at that period, partly because the alchemists commonly described their experiments in vague terms, partly because their false theories prevented them from discovering all the pertinent facts and led them to misinterpret much of what they did observe. For instance, the doctrine of the indestructibility of matter,—that the total weight of a system remains unaffected by chemical changes taking place within it,—now regarded as axiomatic, was not definitely formulated; the material nature of air had not yet been recognized, nor had gases been really differentiated; the process of combustion was not understood, and analytical methods hardly existed.

Boyle's views gained ground very slowly, but the progress of chemistry was hindered for a century by a false theory, the so-called phlogiston theory. According to this view, there is an inflammable principle—phlogiston—which escapes when a substance is burned. For instance, when a metal is burned, phlogiston escapes and a calx or earth remains; on which basis the metal is a compound of calx plus phlogiston, whence it would follow that in order to regenerate the metal, phlogiston must be supplied to the calx by heating with some substance (such as carbon) rich in phlogiston. This theory emphasized the fundamental similarity of all combustion processes, and to that extent was a good and useful hypothesis; but the picture

[3] *Op. cit.*, p. 187.

it presented is almost the exact inverse of the real facts, for we now know that a metal in burning actually unites with oxygen, that the calx or oxide weighs more than the metal, and that the system as a whole has lost energy, mainly in the form of heat—all of these changes having to be reversed in order to regenerate the metal from the oxide. The phlogiston theory, despite its falsity, continued to prevail for a century, during which time it befogged the whole subject and paralyzed the advance of chemical philosophy; the net result being that, until nearly the end of the eighteenth century, the subject was as little clear as it had been a hundred years before, although it had in the meantime been enriched by many new observations of importance, and progress along experimental lines had been quickened by improved technique. This prevalence of a false theory, which hindered progress so greatly, leads one to wonder if some of the hypotheses now commonly accepted do not have a similar inverse relation to the real facts, as was the case with the phlogiston theory; it is this type of question which the promoters of the theory of relativity are in effect asking with respect to some of our fundamental physical ideas.

Another mistaken notion was the material nature of heat. The fact that flames issue from burning bodies led to the view that they were material objects; and so fire was regarded as one of the elements. Even after the overthrow of the ancient ideas of combustion, it was believed that heat, or caloric as they termed it, though devoid of weight, was a substance—an imponderable, in the same category as light and electricity.

Thus, even as late as 1848, in a very interesting *Manual of Chemistry*[4] the author writes:

The first part comprehends an account of the nature and properties of Heat, Light and Electricity—agents so diffusive and subtile that the

[4] Manual of Chemistry on the Basis of Dr. Turner's Elements of Chemistry, by John Johnston (1806-1879), Professor of Natural Science in the Wesleyan University; new ed., Philadelphia, 1848, p. xiii.

common attributes of matter cannot be perceived in them. They are altogether destitute of weight; at least, if they possess any, it cannot be discovered by our most delicate balances, and hence they have received the appellation of Imponderables. They cannot be confined and exhibited in a mass like ordinary bodies; they can be collected only through the intervention of other substances. Their title to be considered material is, therefore, questionable, and the effects produced by them have accordingly been attributed to certain motions or affections of common matter. It must be admitted, however, that they appear to be subject to the same powers that act on matter in general, and that some of the laws which have been determined concerning them are exactly such as might have been anticipated on the supposition of their materiality. It hence follows that we need only regard them as subtile species of matter, in order that the phenomena to which they give rise may be explained in the language, and according to the principles, which are applied to material substances in general.

From this it is apparent that the author did not feel quite sure of his ground, although Rumford's experiments in 1798 had shown that heat could be generated without limit by friction alone; indeed, the question was not determined until the experimental investigations of Joule, published 1843-1849, established the doctrine of the conservation of energy, that heat and work are mutually and quantitatively interconvertible.

Thus, up to nearly the close of the eighteenth century chemistry had not become a science. No descriptions had yet been given which correlated change of properties with change of composition in such a way as to indicate new lines of investigation. Indeed, the conception of chemical composition, as we now understand it, had not taken form, because the phenomena —and in particular, the change of weight—accompanying the transformation of one substance into another had not been accurately observed. From this period date the use of the balance, perhaps the most characteristic single tool of the scientific chemist, and the quantitative analysis of chemical

changes; and with this advance chemistry begins to be a science, with a growing body of definite principles.

In rendering chemistry a science many men bore a part, but the outstanding figure is Lavoisier, born in 1743, beheaded in 1794 because "the Republic has no need of scientists," a view which, though still widely held implicitly, is not now carried to its logical conclusion in the same way as it was then. Lavoisier's *Traité élémentaire de chimie,* published in 1789, is a systematic treatise which transformed the subject. He gave a definite meaning to the expression, "chemical composition"; and recognized that the quantity of matter is the same at the end as at the beginning of every operation. He stated that the object of chemistry is "to decompose the different natural bodies, and . . . to examine separately the different substances which enter into their combination. We cannot be certain that what we think today to be simple is indeed simple; all we may say is, that such or such a substance is the actual term whereat chemical analysis has arrived, and that with our present knowledge we are unable to subdivide further." This quotation shows that Lavoisier had a much better philosophic attitude towards the whole matter than have had many of the chemists since his time; indeed, until recently chemists were so much occupied in accumulating observations that they were prone to neglect the philosophy by means of which alone these multitudinous observations can be correlated.

Lavoisier gave a table of elements, containing thirty-three names, of which twenty-three are still regarded as elements—the definition of a chemical element being that it is a substance which we have not succeeded in breaking up into anything simpler, the atoms of the several chemical elements therefore being, so to speak, the small pieces of tile of different kinds out of which are built up all of the numberless patterns or mosaics which we see about us as diverse kinds of matter. Of the others, five—lime, magnesia, baryta, alumina, silica—are

oxides which, with the experimental means then available to Lavoisier, could not be decomposed. These twenty-three elements, the number known at the end of the eighteenth century, comprise the following: carbon, hydrogen, oxygen, nitrogen, phosphorus, sulphur, antimony, arsenic, bismuth, cobalt, copper, gold, iron, lead, manganese, mercury, molybdenum, nickel, platinum, silver, tin, tungsten, zinc. This list, it will be noted, includes only six non-metals, one of which—sulphur—was known to the ancients though not recognized by them as an element in the modern sense of the term. Of the seventeen metals on Lavoisier's list, seven—gold, silver, copper, iron, mercury, lead, tin—were known to the ancients, though not as elements; most of the others were isolated for the first time during the second half of the eighteenth century. Incidentally it may be mentioned, as an illustration of the slowness with which knowledge is applied, that some of these metals—notably, tungsten, molybdenum, and manganese—were not used technically for more than a hundred years after their discovery; we now value them highly, as their use enables us to achieve results of the greatest importance technically and therefore economically, results which otherwise were unattainable. It is of interest, furthermore, to note that the names of two of these elements—cobalt and nickel—derive from words meaning "the devil," ores of copper admixed with these metals being then considered useless; indeed, we have only learned to make use of such ores comparatively recently. Nickel has been produced on a large scale for a short time, and no large use has yet been made of cobalt, although it is comparatively plentiful.

By the year 1800, twenty-seven chemical elements had been recognized, the four added since Lavoisier being uranium, titanium, chromium, and tellurium; thirty years later, in 1830, this number had been doubled. The discovery of many of these elements (for instance, the metals associated with plati-

num—palladium, rhodium, iridium, osmium) was brought about by the application of more and more careful analytical methods, in the hands of men such as Wollaston and Berzelius—the latter alone adding five to the list.[5] The isolation of others, notably the alkali and alkaline earth metals (potassium, sodium, calcium, strontium, barium), by Davy in 1807, was achieved by a new and powerful method of analysis, namely, the application of the electric current to the breaking up of substances. Davy, after proving definitely by this means that water is composed solely of hydrogen and oxygen, established the fact, surmised by Lavoisier, that the alkalies are oxides of metals; therefore that oxygen, the acid-producer as it had been named (erroneously, as we now know), is a constituent of the alkalies. He was, however, puzzled by ammonia and in particular by the ammonium radicle or grouping[6] which in its salts so closely resembles the alkali metals; and this puzzle was not solved until about 1840, by which time the idea of the existence of similar compound radicles in organic chemistry was beginning to find general acceptance.

From this period dates the usefulness of the atomic theory, first clearly enunciated by John Dalton in his *New System of Chemical Philosophy,* published in 1808. The speculation that matter is ultimately composed of discrete particles, or atoms, had been common in philosophical writings; but it had led to no real progress of knowledge until Dalton showed how the assumption that each element is made up of atoms serves to correlate experimental observations and to suggest new inquiries. On this basis, the myriad substances we see about us are all made up of combinations of a small integral number of atoms of the several elements present, the atoms of each element having characteristic properties, and in particular a characteristic weight. Chemical combination of one element with

[5] See the chronological table of the discovery of the elements, Appendix 3.
[6] See *infra.*

Robert Boyle.

Anton Laurent Lavoisier.

John Dalton

Sir Humphry Davy.

another is the union of an atom of one element with an atom, or a small number of atoms, of the other; this number, in compounds of two elements, seldom exceeds four and is always less than eight, and it is in no wise arbitrary but in accordance with what is now termed the relative valence of the two elements. As a simple case, in the ordinary combustion of carbon (coal) one carbon atom unites with two oxygen atoms, resulting in the formation of carbonic acid gas; or, as the chemist writes it in his shorthand, $C + O_2 = CO_2$. In more complicated structures, the number of elements present may be greater than two, but is seldom greater than five; the total number of atoms making up the structure characteristic of the substance is in some cases large, but in all cases it can be pictured as made up of a number of groupings, each composed of two elements. As a simple familiar instance, limestone ($CaCO_3$) is made up of equivalent amounts of lime (CaO) and carbonic acid (CO_2), and is decomposed into these two proximate constituents in the operation of lime-burning, thus:

$$\underset{\text{calcium carbonate}}{CaCO_3} \quad (CaO.CO_2) = \underset{\text{calcium oxide}}{CaO} \quad + \quad \underset{\text{carbon dioxide}}{CO_2}.$$

Furthermore, the lime, when used as mortar, is slowly reconverted into the carbonate by the action of the carbonic acid always present in the atmosphere. In many chemical processes we are dealing with an exchange of partners, the substances A B and C D becoming A D and B C; for example, hydrochloric (muriatic) acid added to a solution of silver nitrate (lunar caustic) yields nitric acid and silver chloride, the latter appearing as an insoluble white curdy substance; or in symbols, $HCl + AgNO_3 = HNO_3 + AgCl$. This illustrates the fact that the apparent affinity of one kind of atom for another is not the same under all circumstances, and that consequently a

firm and long-standing union of two atoms may be broken up by the entrance of a third under appropriate conditions.

The atomic theory was a very great step in advance, establishing, as it did, the laws and processes of chemistry on a quantitative basis. Progress since Dalton's time has only served to confirm the essential correctness of the atomic theory; indeed, there is now no longer need to call it a theory, for the reality of atoms is no more open to question than that of any other fact of physical science. The atoms are infinitesimally small, so small that, if a drop of water were magnified to the size of the earth, the constituent atoms would be about the size of footballs. Perhaps a more striking illustration is that, if the particles in a cubic inch of air were magnified until they would just pass through a very fine sieve (100 meshes to the inch), this fine sand of particles would suffice to cover a highway extending from New York to San Francisco, and one mile wide, with a layer about two feet deep. We cannot see the actual atoms, it is true, but we can weigh them and measure them and study their characteristics; the same holds true for electricity, which, it may be remarked, is, according to modern views, also made up of units, named electrons, which bear an extraordinarily intimate relation to the structure of the atom itself.

In 1830, as noted above, about fifty-five chemical elements had been recognized, and these include all—with one notable exception, argon, to which we shall refer later—which have yet been found in appreciable quantities in the surface crust of the earth. Since that time the number of recognized elements has been increased by about thirty, most of which, however, are so very rare that only a few grams of them have ever been isolated—in other words, most of them are chemical curiosities kept in small tubes in museums. Indeed, the recognition and isolation of the majority of these elements has been possible only through the discovery, about 1860, of the possibility of spectrum analysis. This elegant method depends upon the fact

that each chemical element, whether in combination or free, gives, when viewed under appropriate conditions, a so-called spectrum made up of a series of bright lines, the positions, or colors, of which are absolutely characteristic. This method of identification is so sensitive that an element can be recognized even when it is present only in very small amount—an amount of the order of one-millionth of a gram; it therefore enables one to learn how to segregate or concentrate an element originally present in such small quantities that no ordinary chemical test would then suffice to detect it. Likewise, by observation and measurement of the spectra of the sun and stars, it has been definitely determined that the elements present in their upper layers are identical with those which make up the crust of the earth and are already familiar to us, with one or two possible exceptions.

In a table (see Appendix 3) have been brought together the several chemical elements now recognized as such, arranged chronologically; the name of the discoverer is also given, as well as the origin of the name assigned to it. It is in many cases far from easy to specify precisely the date of discovery of an element or to know to whom its discovery should most properly be credited; for instance, the existence of the element fluorine had been recognized for a long time before it was actually isolated, whereas chlorine had been isolated many years before it was considered to be an element. The difficulty is especially marked in the metals of the so-called "rare earths" (brought together in the table as Nos. 64 to 76 inclusive), some of which have not yet been isolated as the element itself. The data of the table are those commonly accepted, but no serious independent research on the questions involved was attempted. Nor was it attempted to include all the radio-elements, which now number more than thirty; those given (Nos. 82 to the end) have been, more or less arbitrarily, selected as typical.

In 1868 Lockyer, while examining the solar spectrum, observed a bright line which did not correspond to any element then known, and attributed it to a hypothetical element helium. This element was not recognized on the earth for about thirty years, although Hillebrand had in the meantime, while examining the mineral uraninite, had some in his hands, but, by reason of its inertness, considered it to be merely nitrogen. It was identified by Rayleigh and Ramsay in the course of their investigation of the inert gases of the atmosphere, an investigation which arose out of the observation—originally made, in a sense, by Cavendish, a century earlier—that there is a fractional difference in density between nitrogen prepared chemically and that obtained from purified air by removal of the oxygen. This investigation resulted in the discovery of a family of five new inert gaseous elements, all of which are present in the atmosphere, argon to the extent of about 1 per cent by volume, helium and the others in the proportion of a few parts per million. Argon, therefore, although all around us in enormous quantities,—within a house 33 x 33 x 33 feet there is about a ton of air and consequently some forty pounds or 10,000 liters (400 cubic feet) of argon,—was not recognized, by reason of its inertness; for neither it, nor any of the argon group, has hitherto been made to enter into chemical combination. But this very inertness is now being taken advantage of; in the case of argon, as a filling for electric light bulbs; in the case of helium, as a non-inflammable filling for balloons, a matter which, during the war, was considered so important that large quantities of it were to be separated from natural gas in Texas, with great difficulty and at very large expense. Incidentally, this is an excellent illustration of the results which may follow from scientific work carried on merely to learn about things, and not with any idea of discovering something of particular use; for the possibility of producing helium on a

large scale is a direct outcome of careful observations of the spectrum of various samples of natural gas.

But the greatest interest in helium, from a scientific point of view at least, is in quite another direction, namely, its intimate connection with the phenomenon of radioactivity, or better, with the disintegration of the so-called radio-elements. These radio-elements, the best known of which is radium, first discovered in 1898, differ from the other chemical elements in one respect, but that one very significant, in that they are disintegrating before our eyes. This disintegration, which proceeds at a rate unaffected by any change of temperature or by anything tried hitherto, is accompanied by a continuous emission of energy—a million times greater than is liberated in any change of matter previously known—largely in the form of material particles shot out with great velocity. This energy is so great that one can indeed count the number of particles shot out by observing the flash produced by the bombardment of a suitable screen, as in the spinthariscope, or the luminous watch dial in which the light is the aggregate of the flashes produced by a quantity of radium which weighs only a millionth of a gram. This phenomenon enables us to detect the presence of a small number of *atoms* of a radio-element; whereas the smallest number of atoms of an element which it has been possible to detect by means of the spectroscope or by the most delicate methods of chemical analysis is at least 10^{12}, a number the magnitude of which will be more obvious from the statement that it is several hundred times the total present human population of the world. It is now definitely established that these material particles are helium atoms, and that this disintegration of the radio-elements is an actual transmutation, a transmutation, however, beyond our present powers to control. If we should ever learn to control this atomic disintegration, it would effect a much greater revolution than was caused by the utilization of coal for power; for

in that case the energy derivable from the atomic disintegration of a shovelful of material would be as great as that now derivable from a thousand tons of coal—in other words we would then be possessed of limitless stores of energy. This has not been done yet, it may not be achieved for a long time, it may not be possible; but he would be a rash man who would deny its possibility. The phenomenon of radioactivity is a very striking illustration of the way in which a new method, a new tool of research, may open up a field which otherwise we would not even sense—nay, hardly be bold enough to imagine; and there is absolutely no reason for believing that other equally novel and unsuspected discoveries will not be made in the future.

From the fact that the material particles shot out by a disintegrating radio-element are helium atoms, it would appear that the helium atom is one of the kinds of brick which go to make up the more complex type of structure of the atoms of the heavier elements. Now the two simplest and lightest atoms known are the hydrogen atom and the helium atom; and there is ground for believing that the hydrogen atom also is one of the bricks of the atom-builder. Indeed, recent experiments of Rutherford (1920) indicate that he has succeeded, by bombarding nitrogen atoms with helium atoms, in dislodging hydrogen atoms from somewhere—presumably from the nitrogen atom. If this is confirmed, we shall have to introduce an interpretative reservation into the present definition of an element, according to which a chemical element is a substance not yet resolved into something simpler. This however, is hardly part of the *history* of chemistry; though, one may ask, what is the use of history, beyond being a sort of literary exercise, if it does not enable us to make general predictions as to what is going to happen? For then only will it be a science.

The deduction from experimental evidence that the hydro-

gen and the helium atoms are two of the building bricks brings us back to a very old idea, to the idea that matter as we see it is, or—one would now say preferably—the chemical elements are, made up of one, two, or at most a few, kinds of primordial stuff. The relative weight of the atoms of the several elements can be determined by simple experiments; these atomic weights were usually referred to hydrogen as unity, hydrogen being the lightest known element, but for practical reasons are now referred to oxygen = 16.00, there being only a fractional difference between these two standards of reference. It was early observed that a much larger proportion of these atomic weights approximate to whole numbers than can be accounted for on the theory of chances. From this it was inferred that the hydrogen atom was this ultimate unit; but there were a number of well-established marked exceptions[7] which would not be explained away and so tended to discredit the doctrine. Nevertheless this hypothesis, often called Prout's hypothesis, continued to be a useful one, as it was the occasion of much of the best work on atomic weights; and in spite of the exceptions, it persisted as an aspiration which was rewarded in time by the discovery of the periodic law of the chemical elements, established by the writings of Mendeléeff.

According to this great generalization "the properties of the elements, and, therefore, the properties of the simple, and of the compound bodies formed from them, are in periodic dependence on their atomic weights." In other words, if the elements are arranged in order of increasing atomic weight, we find that like properties recur regularly, and that by this means like elements are brought together into natural groups, *e.g.*, the alkali metals, the halogens, the inert gases. This peri-

[7] These are now showing signs of yielding, in that the elements in question seem to be mixtures of so-called isotopes which have identical chemical properties, and so cannot be separated by chemical means, but differ slightly in characteristic weight.

odic classification had a profound effect in leading us towards the correct value of atomic weight of many elements; and in enabling predictions to be made as to the existence and properties of undiscovered elements, predictions which were completely verified in three cases by the subsequent discovery and investigation of the properties and relations of scandium, gallium, and germanium. But to record all the consequences of this periodic law would be to recount the achievements in inorganic chemistry in the fifty years elapsed since its discovery; suffice it to say that it forced the chemist to cease thinking about the elements as unrelated entities and, instead, to consider them as members of a family or, at the least, as members of a series of related families.

Time has only served to corroborate the essential correctness and usefulness of the periodic classification of the chemical elements; and no evidence has been more conclusive than that derived, within the last few years, from investigations of X-rays and of radioactivity. This work has led to the conception of a characteristic atomic number which changes by unity in passing from one element to its neighbor in the periodic system. It appears, indeed, that this atomic number is really more fundamental than the atomic weight, that all the properties of an atom, save mass and radioactivity, depend upon the atomic number, which is the number of negative electrons (*i.e.,* atoms of electricity) surrounding the positive nucleus at which the mass of the atom is assumed to be concentrated; or rather, that the distribution of the negative electrons on which the ordinary physical and chemical properties depend is a function, and a periodic function, of the units of electric charge on the nucleus, and hence of the atomic number. It is believed that the lightest known element, hydrogen, has an atomic number of 1, helium of 2, lithium of 3, and so on up to thorium and uranium, the heaviest known elements, with atomic numbers of 91 and 92, respectively. If these views

TABLE I

PERIODIC TABLE OF THE ELEMENTS

	GROUP 0	GROUP I	GROUP II	GROUP III	GROUP IV	GROUP V	GROUP VI	GROUP VII	GROUP VIII		
HYDROGEN H 1.008	2 HELIUM He 4.00	3 LITHIUM Li 6.94	4 GLUCINUM Gl 9.1	5 BORON B 10.9	6 CARBON C 12.005	7 NITROGEN N 14.008	8 OXYGEN O 16.000	9 FLUORINE F 19.0			
2	10 NEON Ne 20.2	11 SODIUM Na 23.00	12 MAGNESIUM Mg 24.32	13 ALUMINIUM Al 27.0	14 SILICON Si 28.1	15 PHOSPHORUS P 31.04	16 SULFUR S 3206	17 CHLORINE Cl 35.46			
3	18 ARGON A 39.9	19 POTASSIUM K 39.10	20 CALCIUM Ca 40.07	21 SCANDIUM Sc 45.1	22 TITANIUM Ti 48.1	23 VANADIUM V 51.0	24 CHROMIUM Cr 52.0	25 MANGANESE Mn 54.93	26 IRON Fe 55.84	27 COBALT Co 5897	28 NICKEL Ni 5868
4		29 COPPER Cu 6357	30 ZINC Zn 6537	31 GALLIUM Ga 70.1	32 GERMANIUM Ge 72.5	33 ARSENIC As 7496	34 SELENIUM Se 79.2	35 BROMINE Br 7992			
5	36 KRYPTON Kr 8292	37 RUBIDIUM Rb 85.45	38 STRONTIUM Sr 87.63	39 YTTRIUM Y 89.3	40 ZIRCONIUM Zr 90.6	41 COLUMBIUM Cb 93.5	42 MOLYBDENUM Mo 96.0	43 ———	44 RUTHENIUM Ru 101.7	45 RHODIUM Rh 102.9	46 PALLADIUM Pd 106.7
6		47 SILVER Ag 107.88	48 CADMIUM Cd 112.40	49 INDIUM In 114.8	50 TIN Sn 118.7	51 ANTIMONY Sb 120.2	52 TELLURIUM Te 127.5	53 IODINE I 126.92			
7	54 XENON Xe 130.2	55 CAESIUM Cs 132.81	56 BARIUM Ba 137.37	[57 LANTHANUM La 139.0	58 CERIUM Ce 140.25	59 PRASEODYMIUM Pr 140.9	60 NEODYMIUM Nd 144 3				
	61 ———	62 SAMARIUM Sm 150.4	63 EUROPIUM Eu 152.0	64 GADOLINIUM Gd 157.3	65 TERBIUM Tb 159.2	66 DYSPROSIUM Dy 162.5	67 HOLMIUM Ho 163.5				
	68 ERBIUM Er 167.7	69 THULIUM Tm 169.9	70 YTTERBIUM Yb 173.5	71 LUTECIUM Lu 175.0]	72 ———	73 TANTALUM Ta 181.5	74 TUNGSTEN W 184.0	75 ———	76 OSMIUM Os 190.9	77 IRIDIUM Ir 193.1	78 PLATINUM Pt 195.2
8		79 GOLD Au 197.2	80 MERCURY Hg 200.6	81 THALLIUM Tl 2040	82 LEAD Pb 207.20	83 BISMUTH Bi 209.0	84 POLONIUM Po	85 ———			
9	86 RADIUM EMANATION Em 222.0	87 ———	88 RADIUM Ra 226.0	89 ACTINIUM Ac	90 THORIUM Th 232.15	91 URANIUM X_2	92 URANIUM U 238.2				

should be confirmed—and their success in correlating diverse phenomena makes it certain that the picture they present is one aspect of reality—we shall have nearly returned to the hypothesis of a primordial stuff; for present evidence indicates that the positive nuclei of hydrogen and helium and the negative electron are amongst the units from which the atoms of the elements are built. But this again is history in the making.

The whole series of accepted elements (excepting some of the radio-elements) is given in Table I, arranged according to atomic number; beside the name of the element, the chemical symbol and atomic weight are shown.

From the considerations just outlined it appears that all of the chemical elements as we know them are of a similar order of complexity, since they belong to a series of families; and consequently that any means which will decompose one element will also decompose others. Moreover, the sequence of atomic numbers indicates that only five elements are missing in the series up to uranium, the heaviest element now known and the parent of one of the two series of radioactive elements. Whether elements heavier than uranium exist is open to question; if they do exist, they would presumably be radioactive, and with a shorter life than uranium.

The most common elements in and about the surface layers of the earth are in general elements of smaller atomic number, as is shown by the following estimate of the percentage of the several elements which go to make up the earth's "crust," defined for this purpose as a layer ten miles in thickness.

TABLE II

*The Chief Elements in the Earth's "Crust" in Order of Abundance.**

Element	*Percentage by weight in the 10-mile thick "crust"*	*Atomic weight to the nearest integer*	*Atomic number*
1. Oxygen	46.43	16	8
2. Silicon	27.77	28	14
3. Aluminum	8.14	27	13
4. Iron	5.12	56	26
5. Calcium	3.63	40	20
6. Sodium	2.85	23	11
7. Potassium	2.60	39	19
8. Magnesium	2.09	24	12
9. Titanium	0.629	48	22
10. Phosphorus	0.130	31	15
11. Hydrogen	0.127	1	1
12. Manganese	0.096	55	25
13. Fluorine	0.077	19	9
14. Chlorine	0.055	35	17
15. Sulphur	0.052	32	16
16. Barium	0.048	137	56
17. Chromium	0.037	52	24
18. Zirconium	0.028	91	40
19. Carbon	0.027	12	6
20. Vanadium	0.021	51	23
21. Nickel	0.019	59	28
22. Strontium	0.018	88	38

* Latest estimate by Clarke and Washington, on the basis of a "crust" ten miles thick. Inclusion of the ocean and the atmosphere in the estimate would raise chlorine from 14th to 10th place with 0.20 per cent, carbon from 19th to 11th with 0.18 per cent, and would introduce nitrogen between chromium and zirconium with 0.30 per cent.

From number 25 onwards the x represents a digit in that decimal place, merely to indicate what is believed to be the order of abundance.

See Washington, H. S., Jour. Franklin Inst., Dec., 1920, pp. 776-777.

TABLE II—*Concluded*

Element	*Percentage by weight in the 10-mile thick "crust"*	*Atomic weight to the nearest integer*	*Atomic number*
23. Lithium	0.003	7	3
24. Copper	0.002	64	29
25. Rare earth metals	0.001	140-160	(57-72)
26. Glucinum	0.000x	9	4
27. Cobalt	0.000x	59	27
28. Boron	0.000x	11	5
29. Zinc	0.000x	65	30
30. Lead	0.000x	207	82
31. Arsenic	0.000x	75	33
32. Cadmium	0.0000x	112	48
33. Tin	0.0000x	119	50
34. Mercury	0.0000x	201	80
35. Antimony	0.0000x	120	51
36. Molybdenum	0.0000x	96	42
37. Silver	0.00000x	108	47
38. Tungsten	0.00000x	184	74
39. Bismuth	0.00000x	208	83
40. Selenium	0.000000x	79	34
41. Gold	0.000000x	197	79
42. Bromine	0.000000x	80	35
43. Tellurium	0.0000000x	127	52
44. Platinum	0.0000000x	195	78
	100.000		

From this table it appears that two elements, oxygen and silicon,—the latter wholly in primary combination with the former, the remainder of the oxygen being combined with the other elements,—together constitute three-quarters of the earth's crust; and that the eight most abundant elements make up nearly 99 per cent of the whole.

It is also noteworthy that, of the metals in daily and common use,

only aluminum, iron, manganese, chromium, vanadium, and nickel, appear among those elements that are present in the rocks of the crust in sufficient amount to be commonly determinable by the usual processes of analysis. Such common and "every-day" metals as copper, zinc, lead, tin, mercury, silver, gold, and platinum, antimony, arsenic, and bismuth—metals that are of the utmost importance to our civilization and our daily needs—all these are to be found in igneous rocks, if at all, only in scarcely detectable amounts. Though they are ultimately derived from the igneous rocks, they are made available for our use only by processes of concentration into so-called ore bodies.[8]

The foregoing estimate is based on analyses of rocks occurring in the outer crust of the earth, on a partial investigation therefore of a thin layer, in thickness amounting to only about one-thousandth of the radius of the earth. It is unsafe, therefore, to conclude, as has been done, that the table represents the percentage composition of the earth as a whole; on the contrary, there is evidence directly opposed to this conclusion. For the average density of the crust of the earth is about 2.75, whereas the average density of the earth as a whole, as deduced from astronomical observations, is about 5.5, twice as great, and correspondingly the density of the inner layer must be still higher. Recent work on compressibility at high pressures has made it probable that no pressure would suffice to halve the volume, or double the density, of a rock; that, consequently, the material at the center of the earth cannot be composed of the same proportion of light elements as is the material at the surface. In other words, there is reason for believing that a larger proportion of the heavier elements occur in the interior than are found at and near the surface of the earth; a conclusion which has important connotations with respect to the history and evolution of the earth.

Up to the present, then, the number of known chemical elements is, excluding the isotopic radio-elements, about eighty.

[8] Washington, H. S., Jour. Franklin Inst., Dec., 1920, p. 778.

That is, chemists, in spite of laborious and prolonged efforts, analyzing all manner of material from all quarters of the globe—and even from the heavens in the form of meteorites—have been able to resolve the multitudinous diversity into combinations and permutations of some eighty substances; and these hitherto irreducible minima—the so-called chemical elements—are members of a family, or of a group of families, and so represent the same stage of simplicity or complexity of structure. Knowledge of the structure of the atom is extending rapidly, but it would lead too far afield to go into this absorbing question here.

Development of Ideas Respecting Chemical Combination, Particularly in Organic Chemistry

The chemical elements are not all of the same degree of importance to us, although there are not very many which we could well do without; but there are four, in a sense, of supreme importance, as they are the main constituents of all living matter. These four elements are carbon, hydrogen, oxygen, nitrogen, with which are associated relatively small, but absolutely indispensable, proportions of other elements. For a long time it was thought that the substances which make up living matter—the so-called organic compounds—were associated with some sort of vital force, and so were to be placed in another category from mineral substances—the inorganic compounds. But this distinction was broken down, for the first time, nearly one hundred years ago; it remains now only in the names organic and inorganic chemistry, the term organic chemistry now connoting merely the chemistry of carbon compounds, from whatever source derived.

So long as the idea persisted that the behavior of organic substances is determined more or less by a mysterious vital force, progress, it is obvious, could hardly be rapid; and indeed the rise of organic chemistry as a science may be said to

date from Wöhler's discovery, in 1828, that urea—a typical product of the animal organism—could be made from materials classed as inorganic compounds. Under certain conditions, the molecule[9] of ammonium cyanate, which is a compound of the ammonium radicle (NH_4) with the cyanate radicle (CNO), undergoes a rearrangement, a change of grouping, yielding urea; or as we would now symbolize it

$$\underset{\text{ammonium cyanate}}{NH_4\,OCN} \longrightarrow \underset{\text{urea}}{OC\begin{matrix} \diagup NH_2 \\ \diagdown NH_2 \end{matrix}}$$

Here we have, therefore, two different substances composed of the same atoms, and convertible one into another by appropriate treatment; this instance illustrates the fact that the properties of a compound depend, not only upon the kinds of atoms and number of each present, but also upon the arrangement of these atoms within the molecule. In other words, the behavior of a substance is dependent upon its constitution, just as the behavior of an animal is dependent upon its constitution. But this is to anticipate by some thirty years; for at that time chemists were still a long way from a clear understanding of the matter. The primary reason was a confusion between the atomic weight and the combining weight to be assigned to an element; this confusion resulted in a lack of consistency in assigning a formula to a substance—for instance, water was then frequently written HO—a circumstance which in turn, so to speak, hid the simple relations of the several compounds

[9] The molecule may be defined, for our present purpose, as the smallest portion of a compound which can be conceived to exist alone; for the subdivision, if it were carried further, would break up the compound into its constituent parts. The radicle is a grouping of elements, which reacts as a unit and is like a chemical element in many respects, with the outstanding difference that the radicle can, by appropriate treatment, be decomposed into its elements or altered.

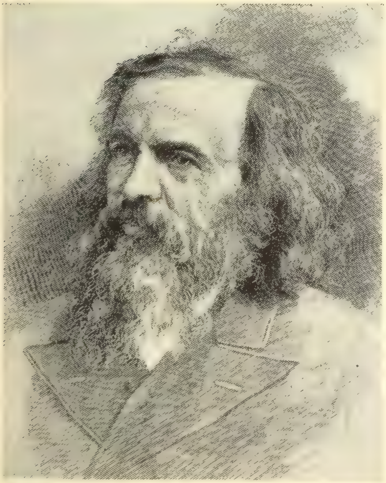
and, indeed, makes it hard for us now to follow much of the writing on chemistry at that time. But it would lead too far into a field of interest only to the chemist, to recount the various steps in the slow advance towards an attainment of consistent ideas of chemical combination and constitution. We can only mention some of the outstanding figures in this advance: Wöhler and Liebig, with their discovery (1832) of the radicle benzoyl; Dumas, with his older type theory (1839), Gerhardt and Williamson, with modified theories of types of formulation of organic compounds.

Liebig's name cannot however be passed over without mention of the enormous influence which he and his teaching had upon the development of the subject. Shortly after becoming professor at Giessen in 1824 he instituted systematic laboratory instruction in chemistry, and Giessen soon became the most famous chemical school in the world, attracting many who were subsequently themselves to become leaders in further development. Still more important was Liebig's pioneer work on the chemistry of the processes of life, both animal and vegetable, work which makes him the real founder of two branches of the subject—biochemistry and the chemistry of agriculture; the development of these two branches is being attended with incalculable benefits to human welfare.

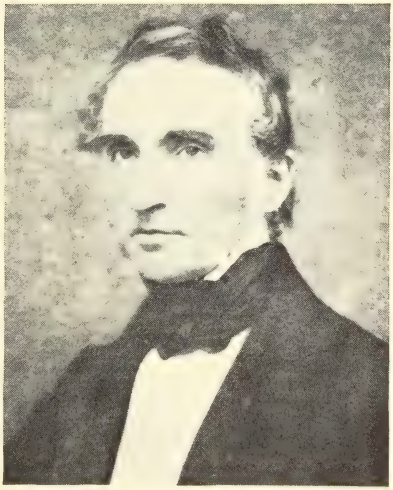
From about 1830 onward, interest in chemistry enhanced steadily, the number of competent workers grew rapidly, and there was a constantly increasing body of facts of observation; but these various observations and the deductions from them awaited reconciliation and interpretation, which came only when the proper theory was developed. This did not happen until 1860 when, at a conference which had been called in the hope of bringing about some more general understanding of the questions at issue, Cannizzaro brought to the attention of the chemical world the hypothesis of Avogadro, showed how on this basis the apparent anomalies disappear, and so clarified

Joseph Louis Gay-Lussac.

Jöns Jakob Berzelius.



Dmitri Ivanovich Mendeléeff.



Justus von Liebig.

the whole situation. Indeed it may be said that modern chemistry dates from 1860, with the enunciation of clear and consistent views with respect to chemical combination, as a direct consequence of grasping the real significance of Avogadro's hypothesis.

From the gas laws of Boyle and Gay-Lussac—namely, that equal changes of pressure, or temperature, occasion equal changes in equal volumes of gases—and from Gay-Lussac's discovery (1809) that two gases reacting with one another do so in simple proportions by volume and that the volume of the product, when gaseous, also bears a simple relation to that of the factors,—reasoning from these, Avogadro, about 1811, was led to the hypothesis: Under the same conditions of temperature and pressure, equal volumes of gases contain equal numbers of molecules. The molecule is the smallest particle of a substance obtainable by *mechanical* subdivision; the atom can be obtained only by *chemical* subdivision of the molecule of which it constitutes a part, and is therefore a particle usually incapable of persisting alone but in most cases existing only in combination with other atoms. This combination may be between like atoms, in which case the molecule so formed is that of the element itself, or between unlike atoms, constituting the molecule of a compound. In either case the same principle holds; with the obvious deduction, as Avogadro showed, that the relative weight of two species of gaseous molecules is measured by the ratio of the weights of equal volumes, under the same conditions of temperature and pressure,—*i.e.*, of the densities—of the two gases. A molecule of the elements which are gaseous under ordinary conditions is made up of two atoms, with exception of the family of rare inert gases which are monoatomic; that of other elements—for example, sulphur—may contain six or more; in all cases there is, as we now know, a progressive dissociation of the molecules with increasing temperature and diminishing pressure, so that at the high-

est temperatures and lowest pressures a large proportion of the molecules are in effect broken up into monoatomic particles.

With the acceptance of Avogadro's hypothesis, the chemist had at last a definite criterion for deciding when he was dealing with really comparable quantities of elements or of compounds; he was enabled to fix the atomic weight definitely, and hence to deduce the correct empirical formula of his compounds. When this was done, many things became clear. For instance, the full significance of the idea underlying the theories of radicles and types, which had been developing for the previous twenty or thirty years, became apparent; and this, in turn, led to the conception of valence, according to which the atom of each element has a maximum saturation capacity with respect to other atoms.

Certain groupings of atoms are so relatively stable that they remain in combination although chemical change is effected in the molecule as a whole; such groupings, known as radicles, react commonly as units and are therefore in many respects analogous to chemical elements, the chief differences being that the radicle cannot commonly be isolated as such and that it can, of course, be decomposed into its constituent elements. The earliest clear example is the ammonium radicle (NH_4), which forms a whole series of salts differing no more from the corresponding salts of potassium (K) and sodium (Na) than these differ from one another; in other words, NH_4 can, in principle, replace K or Na in a whole series of compounds, each of which closely resembles its analogue. Likewise we have a whole series of organic radicles, ranging from the simplest—methyl (CH_3), ethyl (C_2H_5 or $CH_3{\cdot}CH_2$)—up to quite complex groupings—such as stearyl ($C_{17}H_{35}CO$ or $CH_3{\cdot}(CH_2)_{16}CO$)—but all ideally reducible to a small number of types. For instance, consider the following series of

compounds, with the corresponding analogues in which hydrogen (H) is substituted for methyl (CH_3):

$CH_3 \cdot H$ methane, the main constituent of natural gas	$H \cdot H$ hydrogen gas
$CH_3 \cdot OH$ methyl alcohol	$H \cdot OH$ water
$CH_3 \cdot Cl$ methyl chloride	$H \cdot Cl$ hydrochloric acid
$CH_3 \cdot CHO$ acetaldehyde	$H \cdot CHO$ formaldehyde (formalin)
$CH_3 \cdot COOH$ acetic acid (vinegar)	$H \cdot COOH$ formic acid
$(CH_3)_2O$ methyl ether	H_2O water
$(CH_3)_2S$ methyl sulphide	H_2S hydrogen sulphide

This list could be extended indefinitely, in either direction; for a whole series of other radicles can be regarded as derived from methyl by successive substitution in place of one or more of its H atoms, of CH_3 groups or chlorine atoms, or indeed of any other atom or radicle which exhibits the appropriate affinity relations. For instance, we have:

$CH_2 \cdot H$	$CH_2 \cdot CH_3$	$CH_2 \cdot CH_2 \cdot CH_3$	$CH_2 \cdot CH_2 \cdot CH_2 \cdot CH_3$
CH_3	C_2H_5	C_3H_7	C_4H_9
methyl	ethyl	propyl	butyl

and so on, in homologous series, as it is termed; further, C_2H_4Cl, chlorethyl as in $(C_2H_4Cl)_2S$, dichlorethylsulphide (mustard gas); CCl_3, trichloromethyl, as in $CCl_3 \cdot CHO$, trichloraldehyde (chloral), and so on.

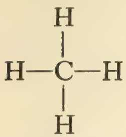
With the recognition of the relationships just outlined, of the existence of radicles related to one another in a simple manner, and of the fact that the multifarious compounds are formed by the possible combinations of the several radicles and elements, it became possible to organize a consistent nomenclature. The advantage of this is obvious; for if to each chemical compound had been assigned an arbitrary name (as has been the case in naming minerals) it would have been

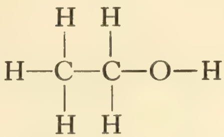
possible to read chemical literature only by memorizing a list numbered now in hundreds of thousands—a task which would have been harder than learning the Chinese characters, and would have resulted in a similar retardation of progress. For certain common substances or common groupings specific names are retained, but in general the name is designed to exhibit the constitution—and therefore the general properties and behavior—of the substance with the least possible memory work; and the chemist gets from these names, in some cases apparently very complicated—*e.g.,* phenyl-dimethyl-isopyrazolone (antipyrin), dimethyl-methane-diethyl-sulphone (sulphonal)—much more information about the substance than the layman gathers from the term "third assistant secretary to the fourth assistant postmaster-general" with respect to the real function of that personage. As simple examples of systematic naming, consider the substances obtainable by chlorinating methane:

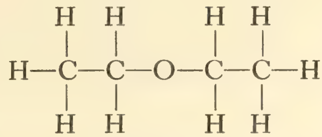
CH_4	CH_3Cl	CH_2Cl_2	$CHCl_3$	CCl_4
methane	chloromethane	dichloromethane	trichloromethane	tetrachloromethane
	(methyl chloride)		(chloroform)	(carbon tetrachloride)

Closely allied to the doctrine of radicles and types is the doctrine of valency, according to which each element has a maximum saturation capacity with respect to other elements. This doctrine developed about the same time, though in somewhat more rigid form than would now be generally accepted. Accordingly, to carbon was assigned the valence 4, to oxygen 2, to hydrogen and chlorine 1, and so on; and it was but a short transition to picture the valence numbers as the number of linkings or bonds with which one atom may hold others, and from this to the writing of graphic or structural formulæ. The graphic formula enabled the organic chemist to represent still more satisfactorily the structure of his substances, and has been an indispensable tool in the subsequent great development

of organic chemistry; the following simple examples will suffice:


methane

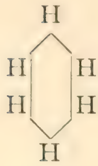

ethyl alcohol

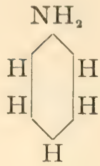

(diethyl) ether

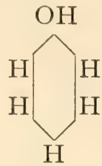
In 1861 appeared the first portion of Kekulé's great textbook which emphasized and illustrated the new views with hundreds of examples. The foundations of modern organic chemistry were therein laid and, what is more important for us here, the date marks the time when the great contribution of organic chemistry to the historical development of the science as a whole was fully rendered.[10]

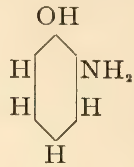
So far we have mentioned only compounds whose structure can be represented by a straight chain of carbon atoms, and grouped under the general name of aliphatic (or fatty) compounds from the circumstance that fats belong to this category. But there is another category, the so-called aromatic compounds, the simplest and typical member of which is benzene, which has the empirical formula C_6H_6. A satisfactory structural formula for this substance was first given, in 1865, by Kekulé, who assumed that the six carbon atoms are arranged in a ring, a single hydrogen being attached to each; and all the subsequent work on aromatic compounds has only served to confirm the usefulness of this hypothesis. One instance only can be mentioned here, namely, that whereas there is only one mono-substitution product (*i.e.,* where one atom of hydrogen is replaced by a different atom or grouping, as in phenol), there are three di-substitution products (designated as ortho, meta, para), which differ by reason of the different relative position of the two substituting groups. This will be evident from the structural formulæ, as now written:

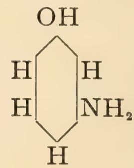
[10] Moore, F. J., History of Chemistry, p. 173.

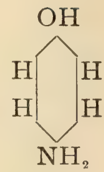

benzene


amino-benzene (aniline)


phenol (carbolic acid)


ortho-amino-phenol


meta-amino-phenol


para-amino-phenol

The long controversies which ended about 1860 in the triumph of Avogadro's hypothesis and the vindication of the atomic theory had been fought out in the organic field, and had culminated in the establishment of the valence theory as the guiding principle in that branch of the science. This gave, perhaps, to organic chemistry a somewhat exaggerated importance—at any rate, the idea that chemical compounds could be visualized as groups of real atoms united by real bonds exerted a remarkable fascination, and young chemists in great numbers began to devote themselves to synthetic studies, attempting on the one hand to prepare from the elements the most complex products of nature, and on the other to make the greatest variety of new combinations in order to find the utmost limits of chemical affinity and molecular stability. The rise of the coal-tar industry and the possibility of preparing from this source so many compounds of practical utility was partly cause and partly effect of this great movement which is going on uninterruptedly at the present day.

If, however, we ask what direct contribution *to the science as a whole* has been made by organic chemistry since 1860 we can hardly give it so high a place. We must rather confess that this branch of the science has lived largely for itself and while it has, during that time, developed a real history of its own which is of fascinating interest to the specialist, its great historical service to chemistry culminated in the work of Williamson, Gerhardt and Kekulé.[11]

Development of Organic Chemistry in the Last Fifty Years

The science of organic chemistry developed, as we have seen, very slowly until consistent ideas as to the mode of com-

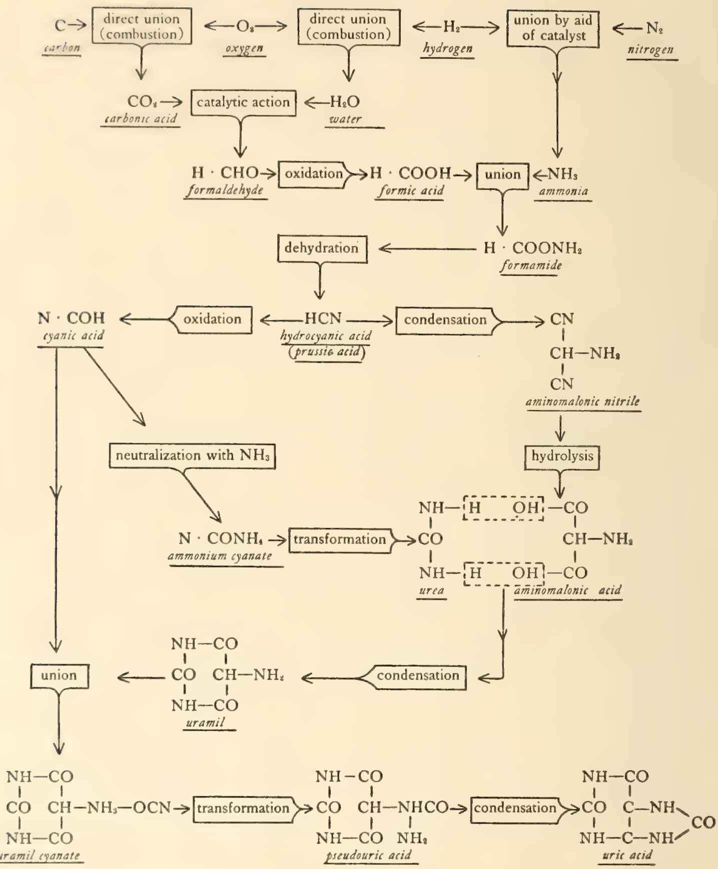
[11] Moore, F. J., History of Chemistry, p. 212; italics mine.

bination of the elements, and consequently as to the structure of compounds, were established; but since then its growth has been by leaps and bounds. Today the organic chemist has prepared, described, and ascertained the constitution of compounds numbering 150,000 or more; amongst these, in addition to a large number which had previously been isolated from natural products, are a vast number never known until built up in the laboratory. Indeed, as soon as he established the structural principles upon which organic compounds are built up, he became an architect and designer of chemical structures, using as units the radicles or groups, and proceeded in his laboratory to learn how to build up such structures. And so it is now possible to synthesize in the laboratory, by a series of operations as indicated in Table III, a relatively complex substance such as uric acid from its elements; or, starting from benzene or naphthalene, the chemist may finish with a dyestuff, a regular skyscraper of a compound whose structural formula fills half a page and whose systematic name requires several lines of type in more than one font.

In this connection it may be remarked that the so-called coal-tar or aniline dyes bear about the same relation to coal-tar or aniline as a steel battleship does to a heap of iron ore, the latter being merely the raw material from which the former is fashioned. Moreover, an artificial or synthetic substance is no imitation or substitute, but is the real thing and indeed is often purer and better than the natural product; synthetic indigo is real indigo, a synthetic ruby is a real ruby, the only difference being that one is produced by what we are pleased to call natural processes, whereas in the other the process is controlled so as to yield a pure product.

The successful synthesis of a substance is usually not possible until its structure has been established, a matter which may require long-continued laborious effort and analysis; even then it may be realized very slowly, for one must learn how

TABLE III



To illustrate an actual mode of building up uric acid from its elements; the general scheme being substantially that followed in the formation of this substance in life-processes. The general character of the several processes denoted by an arrow is indicated; the name of each substance is in italics.

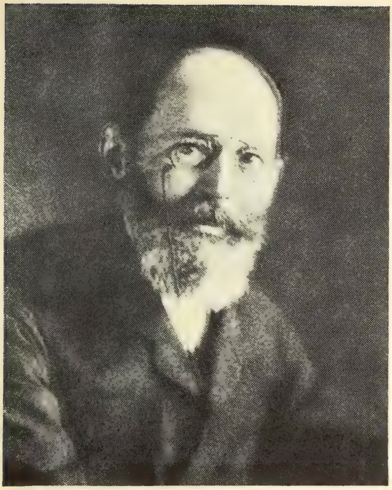
to make his units combine to form the structure desired. Successful synthesis in the laboratory does not imply that this synthesis will directly be carried out on a large scale; the development of an economically feasible scheme of operations requires a time measured in years rather than in months—even in wartime, when considerations of financial economy are secondary and when more effective coöperation can be secured, the interval between preparation by the gram and production by the ton is a matter of many months. Indeed, in some cases—*e.g.*, sugar and rubber—there is no immediate prospect of synthetic production on any large scale, because the material can be built up in the growing plant—the sugar cane or the rubber tree—at a cost comparable with that of the basic raw material required in its artificial production.

The story of even a single achievement in synthesis would be so long and would involve so many technical details and explanations that it cannot be given here; we shall have to limit ourselves to a mention of some of the outstanding examples, premising that these achievements became possible only because of knowledge slowly accumulated by the efforts of many men possessed by a curiosity with respect to the inwardness of things.

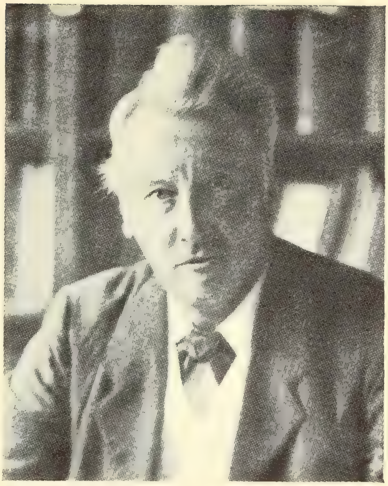
Aniline, discovered first in 1840 as a decomposition product of indigo, was found in coal-tar by Hofmann in 1843; in 1845, after his discovery of benzene in coal-tar, Hofmann could make aniline in large quantities from benzene. In 1856 Perkin, a student of Hofmann, while oxidizing some crude aniline, obtained a dye; this was mauve, the first of the aniline dyes, the starting-point of an industry which has since grown to enormous proportions. In 1868 alizarin, hitherto prepared from madder root, was synthesized, and, within a few years, was being made on a large scale, to the complete displacement of the natural product. Indigo was prepared first in 1870, made from accessible coal-tar derivatives in 1880, but it was not until 1890

that the process was discovered which ultimately proved successful commercially; about 1902 the synthetic indigo came on the world market, and by 1914 Germany was selling over a million pounds a month at about fifteen cents a pound, as compared with a price four times as great ten years earlier. This list of materials made from coal-tar derivatives could be extended indefinitely to include a whole host of compounds, many of which were not known at all until built up by the chemist, used as dyes or drugs, antiseptics or anæsthetics, perfumes or flavors, and now indeed considered indispensable.

About a hundred years ago, Biot observed that a ray of light polarized in one plane has that plane twisted in passing through certain organic substances; and that the direction and extent of this rotation of the plane of polarization is different for different substances. In 1848 Pasteur—who later elucidated the whole question of fermentation and became the father of the science of bacteriology—observed that ordinary tartaric acid rotates the polarized ray strongly to the right, but that certain tartars yielded an acid called racemic acid, identical with tartaric acid in every respect except that it was optically inactive. On further investigation he discovered that this racemic acid is a mixture of two kinds of tartaric acid in equal quantities and having equal but opposite effects on polarized light; and that the crystals of the dextro form and of the levo form differ only as the right hand differs from the left or an object from its mirror-image. Pasteur also found that any organic optically active substance will yield two forms of crystal, left-handed and right-handed, and concluded that in such pairs of substances the arrangement of atoms must in one case be the mirror-image of the other. There the interpretation of the matter rested until 1874, when van't Hoff, and Le Bel, independently, correlated the observations by the discovery that the molecule of an optically active organic compound contains at least one so-called asymmetric carbon atom



Emil Fischer.



Jacobus Hendricus van't Hoff.

Robert Wilhelm von Bunsen.

Louis Pasteur.

—that is, a carbon atom linked to four different groups or atoms—and showed that optical activity vanishes as soon as the carbon atom ceases to be asymmetric. This type of isomerism cannot be readily visualized through a structural formula written in one plane; but van't Hoff made it clear by picturing the carbon atom as a regular tetrahedron with linkages extending outward from the four apices, and by using solid models to represent the compounds. On this basis it is apparent that a molecular structure comprising an asymmetric carbon atom may be either right- or left-handed and that there will be two such stereo-isomers for each asymmetric carbon atom present; and the facts have been found to be in complete accordance with these deductions.

The phenomenon of optical activity and its interpretation on a stereochemical basis have proved of great usefulness, for it has been to the chemist a very powerful tool in ascertaining the constitution of many organic compounds. Particularly is this so in the case of the sugars, which have the general empirical formula $C_6H_{12}O_6$. When Emil Fischer started systematic work upon the sugars, in 1883, practically nothing was known as to their constitution; in 1908, when his collected papers on sugar were published, the complex relationships had been resolved. Fischer had succeeded in determining the structural formula, and in synthesizing each of the important sugars; he had prepared many of the possible stereo-isomers, thereby confirming the usefulness of van't Hoff's theory, and had, indeed, systematized the whole matter. This is only one of his great achievements; for he had simultaneously established the constitution of many compounds of the so-called purin group, a group which includes substances such as caffeine and uric acid. His work on sugars brought in its train the necessity for examining further the nature and properties of substances which bring about the process of fermentation; from this it is but a short step to the proteins, a class of sub-

stances more directly connected with life processes than any other. And in this field likewise, which at the outset presented unparalleled difficulties, Fischer progressed a long way; he was able to break down the complex substances into simpler amino-acids and other nitrogenous compounds, to ascertain the structure of these decomposition products, and by bringing about recombination of these units to prepare synthetic peptides which approximate to the natural products.

The measure of Fischer's achievement in this matter is brought out by a quotation from a short history of chemistry published as recently as 1899:[12]

> Not only the simple formic and acetic acids, but complex vegetable acids, such as tartaric, citric, salicylic, gallic, cinnamic; not marsh gas and ethylic alcohol only, but phenols, indigo, alizarin, sugars, and even alkaloids identical with those extracted from the tissues of plants, are now producible by purely chemical processes in the laboratory. It might appear that such triumphs would justify anticipations of still greater advances, by which it might become possible to penetrate into the citadel of life itself. Nevertheless the warning that a limit, though distant yet, is certainly set in this direction to the powers of man, appears to be as justifiable now, and even as necessary, as in the days when all these definite organic compounds were supposed to be producible only through the agency of a "vital force." Never yet has any compound approaching the character and composition of albumen or any proteid been formed by artificial methods, and it is at least improbable that it ever will be without the assistance of living organisms.

This illustrates again the danger of prophecies as to the limitation of man's powers; for the limitations set are continually being transcended by the genius, and he would be rash who would now set a limit to what may be learned from biochemical investigations, in view of the extraordinary progress made within the present century; but to discuss this fascinating

[12] Tilden, W. A., A Short History of the Progress of Scientific Chemistry, p. 154.

subject is beyond the scope of this sketch of the development of the principles of chemistry.

General and Inorganic Chemistry Since 1860

Compared with the enormous growth of organic chemistry, that of inorganic chemistry was for a long time insignificant. It remained for many years largely in the hands of the so-called practical man, who has been defined as the man who practices the errors of his grandfather; and contented itself largely with descriptions of substances rather than with their interrelations and structure. As one instance among many, it may be mentioned that there has been no real technical improvement in the chamber process of making sulphuric acid—which is the key substance, made by the millions of tons yearly, in all chemical manufacture—since Gay-Lussac invented his absorption tower nearly one hundred years ago; nor does this mean that there is no room for improvement, but merely that it was not sought properly. Indeed, as late as 1900, many chemists considered that but little more, and that not of the first importance, remained to be done in inorganic chemistry; the truth being the exact opposite—that we had then barely scratched the surface of this enormous field. It had not been adequately recognized that chemistry had been dealing in the main with the behavior of a rather restricted range of substances over a narrow range of temperature (say, from somewhat below the freezing point up to 400°) and, practically, at a single pressure—with a mere slice of the whole field, in fact—and that these conditions are quite arbitrary when we consider the whole subject-matter of chemistry.

Nor is the development of inorganic chemistry of subsidiary importance, from any point of view. If judged with respect solely to the monetary value of its products it would be far ahead of organic chemistry, as will be obvious if we recall that it is concerned with the production of all our metals, of

building materials such as brick, cement, glass, and with the manufacture of all kinds of articles in everyday use. One reason for its comparative neglect for so many years is that inorganic chemistry is in a sense the more difficult in that, whereas organic compounds usually stay put and behave regularly—one might say that organic radicles are conservative and conventional—the behavior of many inorganic compounds is more complex, somewhat analogous to that of Dr. Jekyll and Mr. Hyde; another is that the great successes of organic chemistry attracted a majority of the workers. But the main reason is that the proper theories for the interpretation of the phenomena had not been available, consequently proper tools and adequate methods of investigation had not been developed.

The fundamental idea which was lacking is the conception of chemical equilibrium, the importance of which was not really grasped until about thirty years ago and is not yet adequately apprehended by many chemists. The first contribution to this question we need notice dates from 1865, when Guldberg and Waage published the so-called law of mass-action. Their paper may be said to inaugurate the quantitative study of chemical equilibrium, though progress for many years was quite slow. Indeed, at that time the conception of equilibrium was very recent; of the few cases then known, the majority were certain gases which had been observed to expand with rise in temperature in an apparently anomalous manner as compared to the so-called permanent gases; this anomaly was accounted for on the basis that a progressive dissociation of the gas, *e.g.,* ammonium chloride (NH_4Cl) into simpler molecules of ammonia (NH_3) and hydrochloric acid (HCl), takes place on heating and that the constituents recombine on subsequent cooling. Hundreds of instances are now known, all of which are in quantitative accord with the law of mass-action.

According to this law, the extent of chemical action within a homogeneous gaseous system is determined by the "active

mass"—or better, the effective concentration—of each species of molecule taking part in the reaction; this implies that an apparently stationary condition, a state of equilibrium, is finally reached, at which point the tendency of the reaction to go forward is just counterbalanced by the tendency of the reverse reaction. This may be made more objective by an actual example. By the equation

$$\underset{\text{carbon monoxide}}{CO} + \underset{\text{steam}}{H_2O} \rightleftarrows \underset{\text{hydrogen}}{H_2} + \underset{\text{carbon dioxide}}{CO_2}$$

we symbolize the fact that under appropriate conditions in any mixture of the gases CO and H_2O some proportion of the gases H_2 and CO_2 will be formed, and conversely, in any mixture of H_2 and CO_2 some proportion of CO and H_2O will be formed; and the law of mass-action states that the concentrations of the several gases will always adjust themselves so that ultimately

$$\frac{[H_2][CO_2]}{[CO][H_2O]} = K$$

where the symbols $[H_2]$, etc., denote the concentrations of the several reacting species, and K is a constant, the equilibrium constant, the value of which depends upon the temperature but not upon the original amounts of any of the substances. From this it is obvious that, if we know the value of K corresponding to any temperature, we are in position to predict exactly what will happen in any mixture in which this reaction may take place, and consequently to select the conditions under which the maximum yield of any one of the substances may be expected. The usefulness of this is so apparent as to require no comment.

The law of mass-action is but a special case of the general question of equilibrium treated so comprehensively by Willard Gibbs, at that time professor of Mathematical Physics at Yale,

on the general basis of the laws of thermodynamics. These two laws now underlie so much of the reasoning upon which advances in chemistry and physics have been based that we must go back a little to consider them.

The doctrine that heat is an imponderable became finally untenable about 1860, when the work of Mayer in Germany and of Joule in England had finally convinced everybody that heat is a form of energy, and that heat and work are quantitatively interchangeable. This leads directly to the First Law of Thermodynamics, the doctrine of the conservation of energy, that energy is indestructible and uncreatable, that energy, though apparently disappearing, is simultaneously reappearing in another form. The second law in its briefest form is that a thermodynamic perpetual motion is impossible; perhaps I can best convey an idea of it by means of the picturesque analogies of a recent writer:[13]

> There is one law that regulates all animate and inanimate things. It is formulated in various ways, for instance: Running down hill is easy. In Latin it reads, *facilis descensus Averni.* Herbert Spencer calls it the dissolution of definite coherent heterogeneity into indefinite incoherent homogeneity. Mother Goose expresses it in the fable of Humpty Dumpty, and the business man extracts the moral as, "You can't unscramble an egg." The theologian calls it the dogma of natural depravity. The physicist calls it the second law of thermodynamics. Clausius formulates it as "The entropy of the world tends toward a maximum." It is easier to smash up than to build up. Children find that this is true of their toys; the Bolsheviki have found that it is true of a civilization.

These two laws, which had been established largely by the work of Mayer, Joule, Clausius, and William Thomson (later Lord Kelvin), have only been confirmed by all subsequent work; and they are now considered as fundamental as any laws in physical science. The great advance in applying them generally to chemical processes is due to Gibbs, who in 1876

[13] Slosson, Creative Chemistry, p. 145.

and 1878 printed in the Transactions of the Connecticut Academy the two parts of his epoch-making paper "On the Equilibrium of Heterogeneous Substances." Gibbs was, however, so far in advance of his time, and his paper was moreover so inaccessible, that the importance of his work was not recognized for ten years, when it was proclaimed by Roozeboom and began to be used as a guide—almost entirely by Hollanders and Germans—in the interpretation of chemical phenomena. It is hardly too much to say that the very large number of subsequent advances in this field are merely applications and variations of Gibbs' fundamental considerations; that his paper mapped out the lines of advance in a new field of chemical science comparable in importance to that uncovered by Lavoisier. The conception of equilibrium in chemical processes constitutes the central idea of what is commonly called physical chemistry, which, however, would be better termed theoretical or general chemistry, since it deals with the general principles of the science.

To many Gibbs' name is familiar only as the formulator of the phase rule, a qualitative theorem, derived from his thermodynamic discussion of chemical equilibrium, which enables one to sort chemical systems tending to equilibrium into categories, and to state qualitatively what behavior may be expected in each type of system. The phase rule has been of indispensable service in the elucidation of problems as apparently diverse as the constitution of alloys (another large field in which we have done little more than scratch the surface hitherto); the origin of salt deposits in the earth; the separation of potash or other valuable salts from the waters of saline lakes; the relation between different crystal forms of the same chemical substance, as exemplified in many minerals and in the so-called allotropic modifications of the elements themselves (*e.g.*, diamond and graphite; phosphorus, white and red, etc.). Indeed, the service which these doctrines with respect to chemical

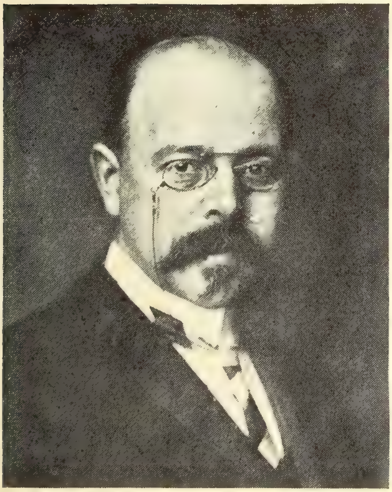
equilibrium have rendered is but a fraction of what they will render to chemical science, and hence to the people at large.

For a long time there had been investigations looking towards a relation between physical properties and chemical constitution. An early instance is the work of Dulong and Petit, who discovered that equal amounts of heat are required to raise equally the temperature of solid and liquid elements, provided quantities are taken proportional to the atomic weights; and this was frequently used as a criterion in fixing upon the proper atomic weight. This is an instance of the necessity of comparing quantities which are really comparable chemically, instead of equal weights; that regularities which otherwise would remain hidden will be apparent when an equal number of chemical units—molecules—are considered. Hence it is obvious that few such regularities would be observed so long as there was confusion with respect to atoms and molecules; but since 1860 there has been continuous progress in this direction, though until very recently chemists had in their comparisons often made insufficient use of chemical units, as compared with the arbitrary unit of weight, the gram. As examples of this type of relationship we may mention: the heat capacities (specific heats) of gases; the molecular volume, the heat-change accompanying combustion, formation, or melting, particularly as applied to homologous series of organic compounds; the relation between constitution and color and other optical properties, etc.

Along with this went naturally the question of the properties of a substance as affected by mixture with another, of solutions in particular. The fact that the boiling point of a solution is higher than that of the solvent itself had long been known, and measurements of the rise in boiling point caused by equal weights of dissolved material had been made; but it was not until 1884 that Ostwald pointed out that this rise is approximately the same, for any one solvent, when computed

Hendrik Roozeboom.

Stanislao Cannizzaro.



Walther Nernst.

Svante August Arrhenius

for equal numbers of molecules dissolved in the same amount of the solvent. The measurements had been mainly of solutions of a salt in water; but in 1886 Raoult extended the observations to other substances and stated what is now known as Raoult's law, which may be considered as the fundamental law formulating the dependence of the general properties of a perfect solution upon its composition; namely, the lowering of the vapor pressure of the solvent is proportional to the number of dissolved molecules per unit of solvent, or as now frequently phrased, the partial pressure of a component of a solution is proportional to its molar fraction, the molar fraction being defined as the ratio of the number of molecules of that component to the total number of molecules present. Soon thereafter van't Hoff gave the thermodynamic relationships between lowering of vapor pressure and raising of boiling point, lowering of freezing point and osmotic pressure; by means of which any one of these may be deduced from another provided that certain constants characteristic of the solvent are known. It was then possible, from such measurements, to calculate the molecular weight of the substance in solution; when this was done, many of the results were anomalous—in particular, the apparent molecular weight of a salt in solution in water was little more than half what one would expect from its formula.

Now it had long been known that certain classes of substances dissolved in water yield a solution which is a good conductor of electricity, and that aqueous solutions of other substances are poor conductors; the former class, called electrolytes by Faraday, comprises salts, acids, and bases (alkalies), whereas the typical non-electrolyte is an organic substance, such as sugar. And it was precisely these electrolytes which exhibited the anomalous molecular weight. To account for this anomaly Arrhenius propounded the theory of electrolytic dissociation, the basic idea of which is that the electro-

lytes, when dissolved in water, dissociate into two or more constituent particles, that these constituents are the ions, or carriers of electricity through the solution, and that each ion affects the general properties of the solution just as if it were an independent molecule. This theory is another landmark in the field of chemistry, for it has served to correlate and systematize a very large number of apparently diverse facts.

It would lead too far to go into the consequences and applications of the theory of ionization; how it enables us to choose the optimum conditions under which to carry out many analytical operations; how it leads to the view that acidity is determined by the actual concentration of hydrogen-ion (H^+), and basicity (alkalinity) by hydroxyl-ion (OH^-), etc. Its usefulness and importance in aiding us towards a real knowledge of aqueous solutions—a knowledge so essential to progress in many lines—is so great as to require no emphasis. And yet the theory is not completely satisfactory, there being still some outstanding anomalies, particularly in connection with the so-called strong electrolytes as typified by ordinary salts; but there is hope that these discrepancies will disappear with the growth of knowledge of electrochemistry.

The fundamental law of electrochemistry was discovered by Faraday prior to 1840, namely, that one unit of electricity transports one chemical equivalent of an ion, irrespective of voltage, temperature, concentration, or other conditions. Later, it was established that these ions move independently of one another, and with characteristic velocities, facts which, with others, were satisfactorily coördinated by the theory of ionization; which in turn led to greatly improved control of practical electrochemical processes, such as electroplating. Again, it had long been known that an electromotive force is set up whenever there is a difference of any kind at two electrodes immersed in an electrolyte, and when two similar electrodes are placed in different solutions, or in solutions of the

same substance at different concentrations. The next step in advance was taken by Nernst, in 1889, who, from thermodynamical reasoning confirmed by direct experiment, deduced the relation between the electromotive force and the ratio of effective concentration of the active ion in one solution to that in the other. Measurement of electromotive force, therefore, under appropriate conditions, yields independent information as to the effective concentration, or activity, of the ions. Nor is this the only application of this principle to the development of chemistry; for it also affords a measure of chemical affinity.

One of the characteristic phenomena accompanying a chemical change is an evolution or absorption of heat; in other words, the amount of heat contained by the reacting system changes with the chemical change. The measurement of this heat change, which may range from a large negative quantity through zero to a large positive quantity, is the province of thermochemistry. Our knowledge of these heats of reaction is largely due to Thomsen and to Berthelot, each of whom started from the supposition that the heat effect is a direct measure of relative affinity; and it was with this end in view that they carried out the very laborious work involved in these determinations. It is now clear that this supposition is erroneous, that the maximum work producible by a reaction, or its free energy, is a truer measure of affinity, the heat effect being an important factor in this maximum work or free energy. The systematic determination of the free energy of reactions, one of the most potent methods being the electrical method outlined above, is an outstanding task of modern chemistry, of consequence to the progress of the science as well as to industrial progress.

Graham, the discoverer in 1829 of the law relating the rate of diffusion of a gas to its density, later made experiments on the rate of diffusion of dissolved substances through animal membranes; this work led him to divide substances into two

categories—the rapidly moving crystalloids, typified by salt, and the slow moving colloids, typified by gum arabic or gelatine. For a long time this distinction persisted, colloids being regarded as somewhat mysterious, rather messy, substances; and it was apparently considered a good explanation of some ill-understood phenomenon to attribute it, if possible, to a colloid. This whole matter received little systematic attention for forty years and only after 1900 did it become evident that we should not speak of colloids as a distinct class of substances, but may speak only of the colloidal state. The characteristic phenomenon is the dispersion of one substance in another, the system being therefore heterogeneous; and the properties of the colloidal system depend upon the kind of particles, and upon their fineness,—in short, upon the nature and extent of the surface of separation of the two phases. In an outline on the present scale one cannot go further into colloid chemistry, except to say that nearly everything remains to be done and that increased knowledge of the subject is fundamental to progress along many lines in biology and medicine, and is also of inestimable importance to all manner of industries, ranging from tanning to pottery.

Closely connected with this, since they also are surface effects, are the phenomena of adsorption and of catalysis, both known in more or less isolated instances for a long time, and both very ill understood. Their importance has been demonstrated recently, the former in connection with the provision of a satisfactory gas-mask, the latter as a means of making certain products—for instance, edible fats out of inedible oils, in the fixation of atmospheric nitrogen, etc. And there is no question but that both phenomena will be made use of increasingly, and that this increase will be accelerated as soon as we begin to understand the principles underlying these phenomena, a matter upon which we are still in the dark. Indeed, even as it is, extension of the use of catalytic methods is proceeding so

rapidly that predictions are being made that we are entering upon what might be called a catalytic age in so far as the making of many chemical products is concerned.

As we have already noted, practically all chemical work, until very recently, had been carried out within a temperature range extending only from 0° up to 400° and at pressures ranging from atmospheric down to, say, 0.01 atmosphere. But the recent extension of these ranges has had so many practical consequences as to require some mention. This extension, though it hardly involves any important new chemical principle, has in a sense been equivalent to one, in that it has forced chemists to consider the subject more broadly and to remember that "ordinary conditions" are quite arbitrary in reference to the subject as a whole. To illustrate, the chemistry at the 1000° horizon, though subject to the same general principles, has to deal with only a small fraction of the compounds familiar to us at the 25° horizon, and is incomparably simpler; at the 2000° horizon it would be still simpler, and at still higher temperatures—as in many of the stars—the elements, at that temperature all gaseous, in place of being combined with one another, would probably be in part themselves dissociating.

Before 1845 Faraday had succeeded in liquefying, by cooling and compressing, many of the gases then known; but a few of the most common gases—viz., nitrogen, oxygen, hydrogen, carbon monoxide, nitric oxide, methane—resisted all his efforts, wherefore they were often alluded to as the "permanent gases." The clue was given in 1861 by Andrews, who showed that there is for each gas a critical temperature above which it cannot be liquefied by any pressure whatever;[14] and the reason for lack of success with the permanent gases was that the lowest temperature employed had been above the

[14] Though, as we now know, it may be solidified by application of sufficient pressure even at temperatures higher than the critical end-point of the liquid.

critical point of those gases. With appreciation of this point and with improvements of technique, resulting in part from theory and in part from practice, success was finally achieved in all cases; all known gases have therefore now been liquefied, and there is only a difference in degree of "permanence" between hydrogen, which condenses to liquid at 30° absolute, and water vapor (steam), which condenses at 373° absolute. The main victories in conquering this region are given in the following table:

LIQUEFACTION OF THE "PERMANENT" GASES

Substance	Date when liquid first obtained	Observer	Liquid Critical Temperature C.	abs.	Boiling Temperature C.	abs.	Freezing Temperature C.	abs.
Oxygen	1883	Wroblewski	—118°	155	—181°	92	—235	38
Nitrogen	1883	Wroblewski	—146	127	—195	78	—215	58
Hydrogen	1898	Dewar	—243	30	—252	21	—248	17
Helium	1908	Onnes	—268	5	—269	4		below 1

To this may be added that liquid air was first obtained by Wroblewski in 1885, was available for research purposes in 1891, and since 1895, with the development of the commercial machine for producing it, has become an industry; it is now indispensable to several lines of work—for instance, wherever very low pressures are required. Incidentally, too, its development resulted in the invention of the vacuum-jacketed, or Dewar, tube which is now a necessary tool in all work at low temperatures and a convenience to the community generally.

With the command of low temperatures, it is now possible to make accurate measurement, *e.g.*, of specific heats, at temperatures not so far removed from the absolute zero. And there is reason to believe that this type of work is going to furnish very valuable information on some moot questions; for instance, on the entropy of substances at the lowest temperatures

and on the applicability of the Nernst heat theorem, called by some the third law of thermodynamics—questions which bear a very intimate relation to the problem of the nature of chemical affinity.

Apart from mainly qualitative work such as that of Moissan with his arc-furnace on the carbides, little accurate high-temperature work was done until about 1900. In the meantime, methods of control and measurement have been developed to such an extent that many types of measurement may be made just as accurately at 1000° as at 100°. This has enabled many equilibria, both homogeneous (usually in gas systems) and heterogeneous (that is, essentially solubilities), to be determined carefully over a wide range of temperature. Such knowledge is essential for many purposes, both practical and theoretical—from the nature of combustion to the constitution of alloys and the mode of formation of minerals and rocks. Very recently high temperatures have been coupled with minimal pressures in experimental work on electron emission and related topics; but this is at the moment usually considered a part of the domain of physics, which has not yet received adequate attention from a chemical point of view. In the field of high pressures, as in that of high temperatures, recent technical progress has made it possible to follow many types of changes with as high accuracy at a pressure of 10,000 atmospheres (*i.e.,* 150,000 pounds to the square inch) as at 10 atmospheres. This is bringing to light phenomena hitherto unsuspected; thus, when the whole range is considered, it appears to be the rule, rather than the exception, that a substance when solidified exists in more than one crystalline form, each stable within a definite range of temperature and pressure. As an instance of this, there are in addition to ordinary ice, at least four other forms of crystalline water, stable at high pressure; and under increasing high pressure the freezing temperature of water steadily rises until at, for instance, a pressure of

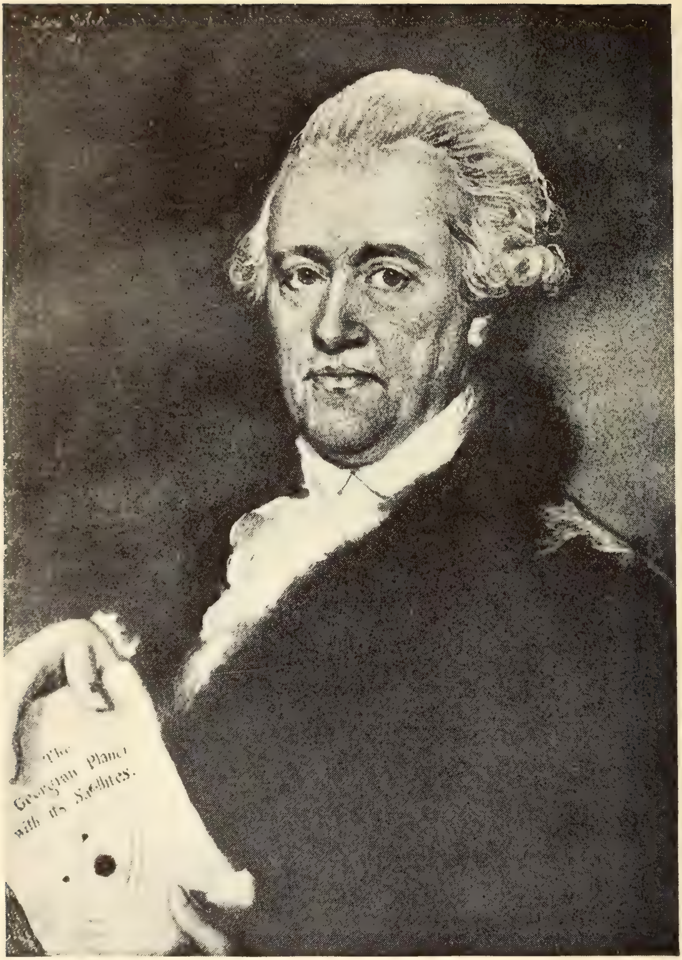
20,000 atmospheres it freezes about 73° (centigrade) higher than its ordinary freezing point.

The phenomena observed at high and low temperatures and at high and low pressures all illustrate the fact that chemistry should not be looked upon as a collection of isolated things which can be manipulated in a sort of magical way, but is to be thought of as, in a sense, almost a continuum, all parts of which are subject to definite laws, still incompletely elucidated; the relative behavior of all substances being controlled by these laws in the same sense as the relative motions of the heavenly bodies are controlled by the law of gravitation.

In this brief sketch of the development of chemical science, many things must remain unmentioned. Yet it must not be supposed that these things are intrinsically unimportant; indeed, an explanation of some puzzling phenomenon may arise out of work in another field, apparently entirely unrelated, each advance in knowledge of any field being that much wrested from the domain of ignorance, and reacting in favor of advances at other points of the line. In particular it has not been practicable to mention the several branches of applied chemistry, for instance, the study of the substances and reactions involved in life processes, with its remarkable advance within the last few years, which would require a chapter to itself; or even analytical chemistry, an essential branch of the subject, which develops with each development of principle, and is to be regarded as including all methods of analysis and not merely the semi-traditional methods applied to a somewhat restricted group of salts of certain metallic bases. The growth of the whole subject-matter may perhaps be gauged from the fact that the 1922 volume of *Chemical Abstracts,* which gives merely brief abstracts of papers of interest to chemists published within the year, contains more than 4300 pages, and that the indexes to this volume alone cover more than 1000 pages closely printed in double column. From this it is obvious

that, even though a large proportion of these papers contain little of real value, one cannot keep abreast of advances in the whole subject but can only hope to have a general knowledge of principles and to acquire a special knowledge of some restricted field.

These principles of chemical science are of its essence and constitute its philosophy; only with development of this philosophy will it be possible to progress in the correlation and systematization of the multitudinous facts of chemistry. The progress of this philosophy, which indeed demands the services of the physicist as much as those of the chemist, is obliterating the line of demarcation between these two sciences. Initially, physics dealt mainly with changes which affect matter independently of its composition, whereas chemistry was concerned mainly with the change of composition; but the physicist and chemist came to meet on common ground for the reason that the quantitative measures of most of the so-called physical properties are intimately connected with the constitution of the substance. And it may be said that the recent very significant advances—dating, say, from the discovery of the X-rays—concern the chemist just as much as the physicist, and that each of them should be conversant with the general mode of thought of the other. Indeed the several sciences have in the past been too far apart from one another, and we should now seek increased coöperation, for it is precisely in the boundary regions between them that the most valuable advances in the immediate future will be made.



SIR WILLIAM HERSCHEL

CHAPTER IV
ASTRONOMY

By FRANK SCHLESINGER
DIRECTOR OF THE YALE OBSERVATORY

ASTRONOMY touches the practical side of our lives in very few places, and not many of us have acquaintance with more than the most elementary facts concerning the skies. This was not always so; if we go back many centuries in the history of mankind we come to a time when a knowledge of the stars was forced upon man, and when a close acquaintance with the apparent motions of heavenly bodies formed an indispensable part of his equipment for his contests with Nature. Watches and clocks were invented yesterday, and even the rudest devices for keeping account of the lapse of hours were contrived comparatively recently. Long before these there were the sun by day and the moon and stars by night from which to tell the time, and very well do these serve this purpose for those who know their habits. In cloudy weather some other expedient was needed, as then only the times of sunrise and sunset could be read in the sky. For those who lived near the sea a supplementary timepiece was afforded by the tides, whose regular recurrence and whose relation to the moon and to the sun must have been recognized by the first of intelligent men.

To measure longer intervals than the day and its subdivisions, the month and the year were adopted, depending respectively upon the apparent motions of the moon and the

sun. The month is not of much natural importance; but it was needed as a step intermediate in length between the day and the year. The latter, on the other hand, is closely interwoven with man's activities. It is and always has been essential to be able to tell how much of the year has elapsed. Printed helps to do this are now as common as clocks. But in ancient times the sky was the only reliable calendar. In its apparent eastward motion among the stars, the great brightness of the sun masks the feeble light of stars in its path and so makes them invisible for a portion of the year. If we watch the eastern sky in the early mornings, we can tell, with an uncertainty of only a day or two, when a bright star first emerges from the dazzling rays of the sun. This is called the star's heliacal rising. Somewhat less than a year later the star is again lost in the rays of the sun in the western sky and is said to be at its heliacal setting. These risings and settings occur accurately at the same time of the year for any particular star. Thus the farmer would learn, out of his own experience, or more likely from instructions that he received from his father, to time the planting of various crops with these heliacal risings and settings of bright stars.

In these and other ways the attention of men of all races was early directed to astronomy. Some knowledge of the science grew up among them before they had acquired the art of recording their doings in any kind of writing, for the very earliest of known records show that astronomy had already made some progress, in some cases to a considerable extent. The most remarkable examples of this are found in China, in India, and especially in Chaldea. Eclipses were predicted many centuries ago, probably at least as early as 2000 B. C., or fifteen centuries before the Golden Era in Greece. The ability to make such predictions shows an astonishing degree of proficiency; to be able to do this even now is popularly regarded as a high achievement of the human intellect. But we must

explain that whereas eclipses can now be predicted with an error of at most two or three seconds of time, the ancients had to be content with merely indicating the day upon which such an event was to be expected. Furthermore, the modern astronomer makes these predictions with a complete knowledge of their cause, starting from the known orbits of the moon and the earth. The ancient predictions are on a very different plane. They were made by rule of thumb, through the empirical discovery of what the Chaldeans called the *saros,* a period of a little over eighteen years, within which eclipses repeat themselves in the same order as in the preceding *saros,* but ten or eleven days later in the year.

Any one eclipse of the moon is visible from about three-fifths of the earth's surface. A prediction made according to the *saros* is almost invariably fulfilled, but we know that this is so only because we can now get reports from every part of the globe. To the ancients, word could come from a very limited area, and thus about one-third of the predictions of lunar eclipses apparently failed. With solar eclipses this difficulty was much greater, as any one of these can be seen on the average from only one-fifth the earth's surface, and thus only occasionally would the prediction of a solar eclipse be verified. These missing eclipses must have increased several-fold the difficulty of discovering the *saros* and make the achievement all the more noteworthy. It is probable that the ancients noticed that after the lapse of three of these periods (about fifty-four years and one month), both solar and lunar eclipses recur under nearly the same circumstances and are visible from about the same area. In any case, it is inconceivable that the *saros* could have been discovered otherwise than from recorded data extending over very many years. It is also unlikely that it was independently detected among three or four different peoples. Probably the discovery was made by the Chaldeans and knowledge of it spread eastward to India and

China, and westward to Egypt and finally to Greece. We cannot help wondering how far astronomy had progressed in Chaldea and whether the people who had discovered the *saros* may not have made other equally striking advances, the record of which has not come down to us.

In addition to their knowledge of eclipses there are many other indications of proficiency among the ancients. But until we come to the Greeks in the sixth century B. C., astronomical inquiry seems to have been concerned more with the question "How?" than with "Why?" The restless and speculative character of the Greek mind showed itself very early in its astronomy, and it is the Greeks who must be accounted the founders of the subject as a true science. To cite only one example: those who preceded the Greeks, for all their success with the prediction of eclipses, do not seem to have been aware that it is the moon that causes a solar eclipse. This idea was advanced by Thales of Miletus (about 640 to 546 B. C.), one of the founders of the Ionian School. From this he was naturally led to conclude that the moon is a dark body and that we see it only because the sun is shining upon it; and from this again he went to the true explanation of the phases of the moon.

Anaximander (611 to 545 B. C.), a pupil of Thales, held that the sun and the moon are much larger bodies than the earth, and thus gave the first intimation of their great distances. Though grossly in error as to the size of the moon, this astronomer must be regarded as the one who took the first of the many steps by which the earth has finally been put into its proper relation to the rest of the universe. Until this suggestion was made, the earth had always been considered as being in every sense by far the most important part of the universe.

Many of the Greek astronomers and philosophers ventured to define the construction of the universe, that is, to set up

cosmogonies. The earliest of these attempts were little in advance of the purely imaginative schemes that had long been in vogue in Asia and in Egypt. Later the Greeks modified their cosmogonies on the basis of new facts and finally evolved systems which are essentially the same as those which modern science demands.

There is a popular impression that it was Columbus who first proved that the earth is round. The fact is that all men of learning knew this to be so many centuries before. All the later Greek philosophers held to this belief, and they had good reason for doing so. After Alexandria was founded in 332 B. C. (and even long before) journeys between Greece and Egypt were frequently made, especially by those who wished to consult the splendid library at Alexandria. It was noticed that in going towards Egypt southern constellations gradually appeared higher in the sky, and that stars that had been barely or not at all visible in Greece were now high above the southern horizon. To such excellent geometers as they were there could be only one explanation, namely that they had traveled over a curved surface. We shall see later that they made use of this principle actually to measure the earth's diameter. Again, they knew that eclipses of the moon were caused by this body entering the shadow of the earth; they noticed the circular edge of this shadow upon the half-eclipsed moon and their geometry again told them that only a sphere could always cast a circular shadow. So as early as about 500 B. C. Pythagoras and his school pictured the earth as a sphere encased on all sides by air, and suspended without tangible support in the center of the universe; a very great step in the history of man's progress.

A century later (about 420 B. C.) an equally important advance was made by Philolaus, a member of the same school. Until then it was supposed that all the heavenly bodies, including the stars, revolve daily about a fixed earth. Philolaus

saw that this motion might be only apparent; accordingly he supposed that all the heavenly bodies, including the earth, revolve around a common center of the universe; that the sun and planets have periods of nearly a year and thus their wanderings among the stars are accounted for; and that the moon has a similar period of one month. But the earth was supposed to revolve in one day around the same center, not very far from it and keeping the same side always turned towards the center.

The last step of all in this sequence was taken by Heracleides about 370 B. C. For Philolaus' revolution of the earth near the universal center, he substituted a simple *rotation* around its own axis.

Two other interesting advances belong to this period. Anaxagoras, who died in 428 B. C. (and to whom instead of Thales some ascribe the true explanation of solar eclipses), declared that the vague markings on the moon are caused by mountains and their shadows. Democritus, about 430 B. C., subscribed to the same opinion. He held also that the Milky Way is composed of many stars, each too feeble to be seen singly. Both these conjectures were verified twenty centuries later when the telescope was first pointed to the sky.

More important than any single discovery or hypothesis made by the Greeks was their initiation of a certain scientific method which even now is one of the most powerful tools of the investigator. Advances are to be made by setting up *working hypotheses* and confronting them with observational data, modifying or rejecting them as new facts may indicate. It was Plato (427 to 347 B. C.) who urged his followers to try to represent the motions of celestial objects by means of circles and spheres, and it was his pupil Eudoxus (408 B. C. to 355 B. C.) who first put this method into effect. He probably did not know and certainly made no use of the notion of a rotating earth that had been developed by the followers of Pythagoras.

He imagined the sun, moon, and planets to be fixed in spheres which revolve within others, all in turn revolving around the earth. By using no less than twenty-seven such spheres he was able to represent well all known motions with the exception of those of Mars and Venus. A few years later these defects were cured by Calippus with the use of six additional spheres. The theories of Eudoxus and Calippus were accepted by the great Aristotle (384 to 322 B. C.), who again introduced additional spheres, bringing their number up to fifty-five. Clumsy and inelegant as these systems appear to us now, they are noteworthy and praiseworthy as being the first attempts to represent celestial motions mathematically.

Aristotle's contributions to all forms of knowledge were very great and no philosopher has ever lived whose word was more respected and revered. For this reason it amounted to a catastrophe (one indeed that was later to cost some men their lives) that he did not adopt the ideas of the Pythagoreans, but held instead to a fixed earth about which even the stars revolve. And so the truths that Greek genius had already discovered were again buried and remained unheeded for nearly twenty centuries, until the labors of Copernicus, Tycho, Galileo, and Kepler finally revealed the true system of the world.

The first astronomer who suffered from the weight of Aristotle's contrary opinion was Aristarchus of Samos (about 265 B. C.). His earliest contribution to the science was a measurement of the relative distances of the sun and the moon from the earth. This he did by estimating when the disk of the moon is exactly at first or third quarter and then measuring the angle between the sun and the moon. In this way he found the sun to be about twenty times as distant as the moon. In reality it is four hundred times as distant. Nevertheless this is a great feat; it was the first attempt to measure the distances of celestial bodies on geometrical principles, and it gave

the first solid intimation of the great distance of the sun and therefore of its great size. With this knowledge gained, a study of the relative sizes of the moon and of the earth's shadow during an eclipse would lead to the conclusion that the sun must be much larger than the earth. To Aristarchus it seemed more reasonable to suppose that the earth attends the sun, rather than that this great and brilliant orb should attend the earth. And so he not only returned to the rotating earth of the later Pythagoreans but went so far as to maintain that the *annual* motion of the sun is only apparent, being really due to the revolution of the earth around it. In this conception Greek cosmogony reached high-water mark. So far as it goes, it presents a picture of the solar system that differs in no wise from that which modern astronomy has proved to be the true one.

The idea that the earth is a sphere had long been an integral part of Greek astronomy. About 200 B. C. an attempt to measure the radius of this sphere was made by Eratosthenes (276 to 196 B. C.). He had been informed that on midsummer day the sun shone directly down deep wells at Syene in Egypt (now the modern city of Assuan, the site of the great dam for the upper waters of the Nile). The sun must therefore have passed directly overhead. At noon of the same day he measured the zenith distance of the sun at Alexandria and found it to be a little over seven degrees, or one-fiftieth part of an entire circumference. This, as we should now express it, is the difference in latitude between the two places. Their linear distance apart was roughly known, chiefly through pacing, to be about 5000 stadia, and as they are about north and south of each other, Eratosthenes concluded that the whole circumference must be 250,000 stadia. Just how close an estimate this is we do not know because there is some doubt as to the length of the stadium employed. According to one value, Eratosthenes' result is almost exact; according to an-

other, it gives dimensions for the earth which are 20 per cent too large. In any case, the experiment yielded a much closer knowledge of the size of the earth than had hitherto been available. This measurement may be regarded as the beginning of the science of geodesy, and it is interesting to note that the method is essentially the same as that of today. Nowadays, however, geodesists measure distances with an error of only one part in a million, and differences of latitude can be ascertained with an error of much less than a second of arc.

To Eratosthenes we owe another precise and important measurement, that of the *obliquity of the ecliptic* or the angle between the plane of the earth's orbit and the plane of her equator. This he found to be 23° 51′, a quantity now known to be only 6′ in excess of the truth.

If we were to set down in order the names of the astronomers in all ages who have contributed most to the science, surely that of Hipparchus would appear very near the top. Of this great man we know practically nothing but what concerns his work, and that has come down to us very indirectly through the word of men who lived centuries after his time. He was probably born at Nicæa in Bithynia, but we do not know when, nor do we know when or where he died. Records of observations made by him on the Island of Rhodes between 146 and 126 B. C. are the only clues to the place and time in which he lived.

Hipparchus proved himself a master of all phases of astronomy, and it is difficult to say which of them owes most to him. In the first place, he improved the construction and design of astronomical instruments, the chief of which were astrolabes (both plane and spherical), a combination of graduated circles provided with sights similar to those still employed on rifles. This enabled him to determine the places of objects in the sky with an accuracy which was in advance of anything that had been attained before, and over which no considerable

improvement was made until Tycho Brahé set up his observatory in Denmark, seventeen centuries later. This advance in accuracy of observation was the basis of Hipparchus' success. With his improved instruments he determined anew the movements of the sun, the moon, and the planets. In discussing these observations, or reducing them as we should now phrase it, he felt the need of a new kind of geometry suitable to the sphere. For this purpose he proceeded to develop the subject of spherical trigonometry, and this feat alone places him high among great mathematicians. Next he was led, as Eudoxus and others had been before him, to represent the observed motions in the sky by mathematical devices, and here again he succeeded nobly.

The most important discovery made by Hipparchus, and perhaps the one that arouses the most admiration on the part of modern astronomers, is that of the *precession of the equinoxes.* Less technically expressed, this is the motion of the axis of the earth in space. If this axis is prolonged to the sky the piercing point is the *pole of the heavens,* around which all the stars seem to revolve in their nightly courses. Hipparchus' discovery consisted in showing that the pole of the heavens is not always the same, but that it moves slowly among the stars, describing a vast circle and coming back to its starting point after about 36,000 years. This is the value he assigned, now known to be about 40 per cent in excess of the truth. So slow is this motion that it would have been impossible for an astronomer, provided with such instruments as Hipparchus had, to detect it within the span of one man's years of activity. He discovered this motion by comparing his own observations with those made by Timocharis a century and a half earlier. This is the first example of a kind of coöperation of which the history of astronomy now has many to offer, a coöperation between the present and the past. Many of the phenomena of the skies unfold so slowly that it is hopeless to try to detect

Nicolaus Copernicus.

Tycho Brahé.

Johann Kepler.

Edmund Halley.

them, much less to measure them, in a single generation. Thus many an astronomer has been called upon to make observations which he knows very well cannot bear fruit until long after his death. In this instance it was Hipparchus who was permitted to pluck the fruit. But he more than repaid the debt; for very many years after his death, down indeed to the time of Halley in the eighteenth century, his own observations were appealed to again and again and formed the basis of later contributions to our knowledge.

Long before the time of Hipparchus the Chaldeans had fixed the length of the year at 365¼ days, which is only eleven minutes too long. All the nations that came into contact with the Chaldeans borrowed much of their astronomy, and among other things adopted this value of the year. Hipparchus was the first to learn that it needed a slight correction, which he placed at six minutes, leaving his year still five minutes too long. This outstanding error in the length of the year accounts for Hipparchus' error in his determination of the rate of precession. The error is not a great one, especially when we consider the character of the observations from which it was discovered; if, however, Hipparchus had used the true length of the year he would have derived a value for the precession that is almost exact.

The appearance of new stars, objects that blaze forth suddenly and temporarily where no stars were visible before, has always played a most important part in stimulating researches in astronomy. One of these very rare objects appeared in 134 B. C. and was observed by Hipparchus. It led him to reflect on the possibility of the temporary character of other stars, and this gave rise to the first catalog of stars. Hipparchus measured the positions of 1080 stars and in addition gave an indication of their brightness by assigning them to six magnitudes, the brightest being called the first magnitude, and the faintest the sixth. This method for recording the brightness

of stars, modified to meet the necessities of modern accuracy, has persisted to our own times.

In the problem of representing the motions of the sun and the moon geometrically, Hipparchus discarded the *spheres* of Eudoxus and adopted instead a much simpler system of *circles,* a device that had been suggested by Apollonius, the famous mathematician. It is to the latter that the invention of epicycles is due, these being circles in which the sun or other body is supposed to revolve, its own center revolving in turn in the circumference of a second circle, called the deferent. Hipparchus used this device to represent the motions of the sun and the moon. He also invented the eccentric, a circular orbit whose center is not at the earth, but removed from it by a small distance called the eccentricity. In this way he was able to represent fairly well all the characteristics of the motions he had observed, especially the inequality that he had discovered in the length of time that the sun remains respectively north and south of the equator. With his better knowledge of the apparent orbits of the sun and the moon, Hipparchus was enabled for the first time to compute eclipses on a strictly mathematical basis, and to predict them with a much higher degree of precision than had hitherto been possible.

After the death of Hipparchus nearly or quite three centuries elapsed before any important addition was made to the science. This brings us to Ptolemy, the last of the Greek astronomers, of whose life we know almost as little as we do of Hipparchus'. He lived at Alexandria in the middle of the second century. His great work is the *Syntaxis,* better known under its Arabian title, the *Almagest.* It is this book that has preserved for us the names and deeds of the earlier Greek astronomers, and especially those of Hipparchus.

Ptolemy's admiration for his great predecessor amounted to reverence and the larger portion of the *Almagest* is taken up with an account of Hipparchus' work and with its continua-

tion. Hipparchus had devoted much time and thought to the representation of the orbits of the sun and the moon. Though he had industriously observed the planets, he had not attacked seriously the problem of defining their motions. This was the great task to which Ptolemy devoted himself, and it is one that required not only an enormous amount of labor, but mathematical ability of a very high order. For it must be remembered that Aristotle's cosmogony, adopted by all but one of his successors and even by Hipparchus, now held the field unchallenged; it is easy to see that the problem of representing the motions of planets by means of circles centering about the earth (when in reality these motions center around the sun) is one of great difficulty. The details of Ptolemy's solution would be out of place here; it must suffice to say that by means of epicycles, deferents, and eccentrics he succeeded in representing well the observed positions of all celestial bodies. The greatest difference between his theory and actual observations amounted to 11′, or to about one-third the angular diameter of the moon.

The *Almagest* refers to numerous observations that Ptolemy himself had made. From his observations of the stars, he states that he confirms Hipparchus' value of the precession, which is now known to be 40 per cent too small. As Ptolemy had the benefit of three additional centuries over which the observations extend, it seems curious at first sight that this inaccuracy should have escaped him. Some writers have gone so far as to suggest that in spite of his statements to the contrary, Ptolemy did not make original observations, but merely brought Hipparchus' observations up to his own date by applying the erroneous value of the precession. Just a century ago Laplace cleared Ptolemy of this suspicion, but it still persists to a certain extent. The explanation is that with such data as the ancients possessed the amount of precession that is deduced depends upon the length of the year that is adopted.

Now Ptolemy did not attempt to determine the latter quantity but simply adopted Hipparchus' value, which as we have already said, is about five minutes too long. These two errors balance each other. Under these circumstances, had Ptolemy derived a value of the precession that differed essentially from that of Hipparchus, then only would there have been any occasion for suspicion.

In addition to his great work on the orbits of the planets, we owe to Ptolemy two important discoveries; he was the first to detect atmospheric *refraction* (which makes objects appear a little higher in the sky than they really are) ; and the *evection* of the moon, a deviation from uniform speed of revolution about the earth.

Although three centuries separate Ptolemy from his predecessor, a very much longer interval elapses before the advent of a worthy successor. After his death we hear no more of the cultivation of astronomy in Europe or by European peoples, until the Dark Ages are past and the revival of learning in Europe is in full swing. In the interim we must look to Asia for the little progress that was made. A survey like the present can make no attempt at anything like completeness, and we shall lose nothing in the continuity of the narration by passing over the labors of all who came between Ptolemy in the second century and Copernicus in the sixteenth.

Niklas Koppernigk, or Nicolaus Copernicus in the Latin form, was born at Thorn in Prussian Poland in 1473, in a house that is still proudly preserved. His father was a merchant of unusual attainments and his uncle was Bishop of Ermland. They taught the boy Greek and Latin and afterwards sent him to the University of Cracow. Here he developed strong mathematical tastes and became proficient in the classics. From the university he returned to his uncle's diocese in Prussia and spent most of his remaining years in the city of Frauenburg, where he died in 1543 at the age of seventy.

Copernicus' contributions to astronomy are wholly on the theoretical side. He constructed some astronomical instruments and made a few observations with them; but in these he was not very happy, falling far short of the standard of precision set by Hipparchus so many years before. His fame rests upon his *De Revolutionibus Orbium Cœlestium,* published just before his death, by far the most important work on astronomy since the *Almagest.* The thesis of this book is the simplification that is brought about by assuming that the daily motions of the stars and all other celestial objects are due to a rotation of the earth on its axis; and that the annual motion of the sun is only apparent, being due to an orbital revolution of the earth around that body. In other words, he supposed the sun and the stars to be stationary, and that all the planets, including the earth, revolve around the sun, the moon alone attending the earth.

It was only on the score of simplicity that this scheme could be urged in that age. The facts presented by the senses seemed to be against it, the authority of Aristotle was against it, the *Almagest* was against it. Most important of all, men of both creeds in Europe (for the Reformation had already begun) declared the new theory to be contrary to scripture. That it did introduce a great simplification in the mathematical representation of observed motions there could be no denying. It was still necessary to have recourse to the epicycles, deferents, and eccentrics, but their number was smaller than in the Ptolemaic system and there was better accordance between theory and observation.

It cannot be claimed for Copernicus that he established the system that bears his name, and which he so ably sets forth and expounds. Confirmation of this hypothesis had to wait a full century, until the advent of Kepler and Galileo. In the interval still another system of planetary motions was set up by Tycho Brahé.

Tycho was born in 1546 (three years after the death of Copernicus) at Knudsturp, then in Danish territory, now in the extreme southern end of Sweden. His father was a nobleman of some consequence and Tycho was the eldest son. Accordingly he was sent to the Universities of Copenhagen and Leipzig, with a view to preparing him for dealing with affairs of state. But Tycho was emphatically a man with a personality. He did not take kindly to this plan and instead devoted much of his university activity to the study (secretly for the most part) of mathematics and astronomy. At the age of twenty he lost his nose in a duel and thereafter wore an artificial one of brass. Some years later he managed to strain relations with his family by contracting a marriage that they thought beneath him. At the age of thirty his reputation as an astronomer was such that King Frederick II of Denmark built for him a magnificent observatory on Hveen, a small island in the Sound just west of the Swedish coast, now belonging to Sweden. This observatory, Uraniborg, the ruins of which are carefully preserved and pictures of which have come down to us, was a veritable castle. Here Tycho spent twenty stormy years, but very fruitful ones nevertheless. His royal patron having died, and the new king (or his ministers) having less vision or possibly less patience than the old, Tycho finally deserted his beloved Uraniborg in 1597. Two years later he found a second admiring patron in Emperor Rudolph II, who installed him and his instruments fittingly in a castle near Prague. But only two years remained to him in which to enjoy his new home; there he died in 1601 at the age of fifty-five.

Tycho's great achievement was the improvement that he made in methods of observing. His instruments were built on so generous a scale that some of his graduated circles showed a mark for each minute of arc, and this small quantity was about equal to the average error of one of his observations. It was not only in the actual observing that Tycho excelled

those who had preceded him; he corrected his observations for all known errors (refraction, for example) with great care and thoroughness. He seems to have been the first to recognize the advantage of repeating observations several times in order to get rid, as far as possible, of accidental errors. Finally, in their number and continuity his observations are altogether unprecedented.

Tycho saw the great merits of the Copernican system and also felt the weight of the objections against it. The heaviest of these was furnished by his own observations. Aristarchus had found that the sun is about twenty times as far away as the moon; Ptolemy had determined the distance of the moon to be about sixty times the radius of the earth, and so the sun's distance must be more than one thousand such radii, a quantity that even to us today is unthinkably great. If the earth is really traveling around the sun, then when we observe the same stars at opposite times of the year our point of view has changed by twice this great distance, and there should be a perspective displacement called *parallax*. But Tycho's accurate observations, some of them made for this express purpose, showed not the slightest trace of such parallax, and he was certain that no such effect as great as $1'$ could have escaped him. In other words, he was confronted with the alternative of supposing that the earth is stationary, or that the distances of stars were more than 7000 times the distance of the sun, and therefore more than 7,000,000 times the radius of the earth. The latter seemed to him (and to many competent contemporaries and successors) to be absurd.

To meet this objection as well as others of a physical character to which the Copernican system seemed open, he modified the latter as follows: the sun and the moon are supposed to revolve around a fixed earth and the planets to revolve around the sun. Except for the parallax of the stars this system is geometrically the same as the Copernican; that is, the relative

positions of any two objects at any specified time are the same in the one as in the other.

Tycho's system has been severely dealt with by later writers, who refer to it with such adjectives as "grotesque" and "unfortunate." Viewed, however, from the standpoint of contemporary knowledge, the system had something in its favor. It represents well the observed facts of that day, and this is the real test of a useful hypothesis. As science progresses, less and less stress is laid upon so-called laws of nature. We have learned to recognize that each advance is to be regarded as a closer approximation to the truth, and that perhaps no advance can quite bring us to absolute exactness. The first thing then that we expect of systems, hypotheses, and theories is that they shall conform to the facts.

Whatever our judgment as to the merits of Tycho's cosmogony, his fame as one of the greatest of astronomers is assured by his practical work. He reviewed and improved all the fundamental data of the science, with the single notable exception of the distance of the sun. Like Hipparchus he constructed a catalog containing the positions of about one thousand stars and this work remained the authority in its field until that of Flamsteed appeared a century later. Like Hipparchus, too, Tycho had the good fortune in 1572 to witness the outburst of a new star; indeed, this occurrence is said to have decided him to devote his life to astronomy. He was also lucky in the number of bright comets that appeared in his time, his observations of these objects forming a precious heritage to succeeding astronomers. He was the first to show that comets are not in our atmosphere but far beyond. He discovered two *perturbations* in the moon's motion, the *annual equation* and the *variation*. Comparing his observed places of the planets with the accepted tables he noticed discrepancies which he recognized were due to the imperfection of these tables. Perhaps if he had not died so comparatively young he

might have attempted to reconstruct these tables, but that task was reserved for his young friend and pupil, Kepler, whose work was destined to put the science on a new footing.

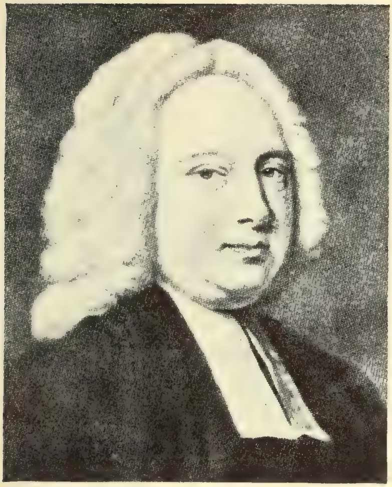
John Kepler must be ranked with Hipparchus, Galileo, and Newton as a leader in the history of the science. Laplace speaks of him as one of those rare spirits that nature gives to science from time to time for the purpose of causing the work of many centuries to blossom. He was born at Weil in Würtemberg in 1571 and was accordingly twenty-five years younger than Tycho. He got his schooling at Maulbronn and Tübingen and taught for a time at Gratz. A Protestant in a community predominantly Catholic, at a time when religious feeling was at its height, he fled to Hungary, finally accepting in 1600 Tycho's invitation to join him at Prague. On the death of Tycho the next year Kepler succeeded him as astronomer to the Emperor and came into possession of all his wealth of observations; he was the one man on earth to whom this inheritance should have come. Kepler did not get Tycho's instruments, but perhaps this was fortunate rather than otherwise, for their possession might have taken away from him and from the world some of the precious years that he devoted to theoretical work. Even as it was, the undisturbed quiet and freedom from petty tasks that are so essential to sustained intellectual effort were only rarely his. The religious unrest that marked the time laid a heavy hand upon him and several times compelled him to seek a new home. Throughout all the later years of his life he was confronted with the problem of earning a living without having to neglect his real work. More than once he was driven to the practice of astrology, an expedient that he must cordially have hated, whatever his real opinion may have been as to the validity of astrological prediction. His life was cut short as the result of a long and severe journey on horseback to Regensburg, whither he had come to try to collect his arrears in salary as astronomer to the Emperor. He

died in 1630, at the age of fifty-nine. Surprising to relate, an inventory of his effects showed that he was by no means a poor man.

Kepler began his work on Tycho's observations of Mars, first attempting to represent them, as all his predecessors had done, by means of the timeworn epicycles, deferents, and eccentrics. The best he could do left considerable discrepancy between his theory and the observations, the differences running as high as 8′. He knew that so large an error in Tycho's work was not admissible and so he undertook, as he said, out of those 8′ to reconstruct the universe. It was in this way that he was finally led to what is known as Kepler's first law, that the orbits of the planets are ellipses with the sun at one focus. We can imagine his joy when he found that with the elliptic orbit the large discrepancies melted away not only in the case of Mars but for the other planets as well.

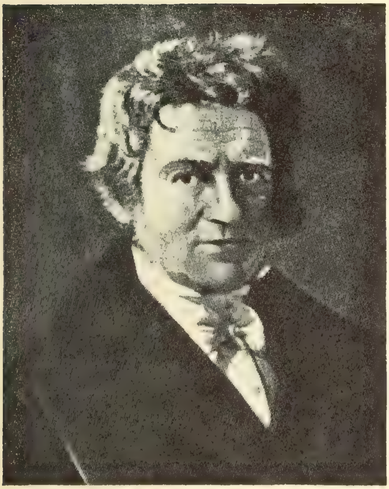
It had been long recognized that the angular speed of a planet around the sun is not uniform. Kepler now tried to discover the law of this motion when the orbit is an ellipse. Again after long and patient trial he discovered his second law, that the line joining a particular planet with the sun sweeps over equal areas in equal times. These two laws were published in 1609 in his book, *Commentaries on the Motion of Mars.* Ten years later he announced the third of his laws in a book entitled the *Harmony of the World.* This law relates the periods of the various planets to their distances from the sun; he found that the squares of the former are proportionate to the cubes of the latter.

It is difficult to conceive how startlingly new these discoveries were. The history of almost every great advance reveals that many men have contributed their quota, though it is given to one man to set the capstone that finishes the structure. In this respect Kepler's work is almost unique; perhaps no other like edifice in the whole history of science is so



James Bradley.

Pierre Simon Laplace.



Friedrich Wilhelm Bessel.

John Couch Adams.

completely the product of one hand. That planetary orbits must be circular was taken for granted by everyone from Plato down even to Copernicus, who had no hesitation in throwing over accepted notions in other respects. It was not that the ellipse and similar curves were unfamiliar, it was simply because circularity was as much a matter of scientific creed then as, for example, conservation of energy is today.

Kepler's laws were by no means his only contributions to astronomy, but to turn to his other work is an anticlimax, important as these researches are. Starting with his three laws, he derived anew the motions of all the bodies in the sky and set down the rules and data that made it an easy matter to compute the position of any of them long in advance. This work was issued near the end of his life as the *Rudolphine Tables,* in honor of his and Tycho's imperial patron. They held the field for a century, until the application of the telescope afforded data more accurate than Tycho's and made possible the calculation of orbits with greater precision. He was the first to show that the sun was more distant than had been supposed by every astronomer since Hipparchus, but Kepler's own estimate still fell far short of the truth. He was among the first to notice the corona, the beautiful light that surrounds a totally eclipsed sun, and the first to assign its origin correctly as a faint but permanent appendage of the sun. He wrote an important work on comets, bodies that he mistakenly supposed to move through the solar system in straight lines. He explained the fact that the tails of comets always point away from the sun by supposing that the light of the sun forms the tail by driving particles out of the head, an explanation that is surprisingly like the one that has only recently come into favor.

Very few investigators in describing their work lead us over the path that they have actually followed. It almost always happens that once having reached the goal, the new point of

view reveals short cuts that had escaped attention, and it is these short cuts that most investigators like to describe. Kepler's books are delightful exceptions to this; he frankly records his failures as fully as his successes and lets us see all the mental processes by which he finally arrives at his results. It is encouraging to the student to see how many false trails so great a man had to explore before finding the road to his destination.

Few men have had the patience and perseverance to go through so great a mass of routine computing, not only without the aid of others but without any of the mechanical helps that are now so familiar. News of Napier's invention of logarithms, together with the first logarithmic tables, reached him only after most of his work was done; and so he benefited little from a device which, as Kepler himself said, triples the life of an astronomer.

Kepler was a man of wonderfully active imagination. It was this quality that was the essence of his success and led him to consider all manner of possibilities; but the same quality often led him astray and there is much chaff among the wheat. It is a pity that this is so; but after all we judge a poet, a painter, a musician by his best, and why not Kepler?

Up to now astronomy had been on an empirical basis and could not be otherwise until the science of physics should be as thoroughly recast as astronomy had now been through Kepler's laws. The revolution in physics did not tarry long; indeed, it was begun in Kepler's time, by Galileo, born at Pisa in Italy in 1564, seven years before the birth of Kepler, and eighteen years after that of Tycho. It is something of a coincidence that three astronomers so great as these should have lived at the same time. Galileo never met either Tycho or Kepler, but it is pleasant to know that with the latter he exchanged letters and that the two held each other in high re-

gard. Galileo survived Kepler by twelve years, dying early in 1642 in his seventy-eighth year.

The story of Galileo, and especially of the later years of his life when the dreadful Inquisition all but crushed him, occupies an important place in the history of intellectual development and of intellectual freedom, and is too well known to warrant repetition here. Nor do we need to recount his work regarding the laws of motion, which has been referred to in the chapter on Physics. It suffices to say here that making use of a new method in physics, the testing of hypotheses by means of experiment, he broke as completely away from the physics of Aristotle and his school as Copernicus did from the astronomy of that school.

It is not known who first devised a telescope; perhaps it was Roger Bacon in the thirteenth century, a pioneer long in advance of his time in several matters. Telescopes are described by Digges in England and Porta in Italy in the middle of the sixteenth century. Certainly it was not Galileo who made the invention; he heard in 1609 that Lippershey and other Dutchmen had the year previous constructed a combination of glasses that made distant objects look near. Acting upon this hint he succeeded in working out the manner in which this could be done, and soon constructed a telescope that magnified thirty diameters. Galileo does not even seem to have been the first to point the telescope to the skies, though he was the first to understand what he saw there. Discovery after discovery of the most startling character followed in rapid succession. He found the moon to be largely covered with rugged mountains (thus confirming the guess that Anaxagoras had made twenty centuries before) and succeeded in correctly measuring the heights of some of them. Similarly he confirmed an equally old conjecture of Democritus when his telescope showed that the milky way is made up of a myriad of faint stars. Next, early in 1610, he discovered four moons of Jupiter, revolving

in from two to sixteen days. No argument bearing upon the validity of the Copernican system had so great an effect upon public opinion as this discovery. The opponents of this system had maintained that if the earth were truly revolving around the sun then the moon would soon be left behind the earth. But here was Jupiter attended not merely by one moon but by four, and all of them managing somehow to keep up with Jupiter in her twelve-year journey around the heavens.

There still remained the argument that Tycho had emphasized, the absence of measurable parallax in the positions of stars. Reflecting upon this circumstance, Galileo hit upon a method for testing the presence of parallax that is much more delicate than those used up to that time. Tycho, for example, had attempted to find such a parallax substantially from changes in a star's altitude at opposite seasons of the year. Galileo's telescope revealed faint stars in the neighborhood of every bright one, and these he inferred must on the average be farther away. Now all the stars in the field of view would be affected by some parallactic shift, but the nearer ones to a greater extent than the distant; as such relative or *differential* shifts can be detected with much greater facility than the *absolute* changes sought by Tycho and others, here was a method that held out some promise of success. This is essentially the method employed today, but so distant do the stars prove to be, and so small their parallax, that more than two centuries elapsed after Galileo's proposal was made before the art of measuring had reached the degree of perfection necessary to reveal this perspective displacement for even the nearest of the stars.

Galileo shares with several others the honor of discovering spots on the sun. These objects seemed greatly to offend the sense of propriety of some of his contemporaries, and attempts were made to keep the sun immaculate by maintaining that the so-called spots are planets revolving near the sun's

surface. But Galileo showed that they are on the sun's surface and that their motions could only be explained by a rotation of the sun around an axis in a little less than a month.

Galileo's telescope showed that Venus presents phases similar to those of the moon, and that Saturn is attended by a curious appendage, the nature of which greatly puzzled him. He also discovered the *libration* of the moon. This body rotates on her own axis in the same time that she revolves around the earth and always presents the same face to us. But as the rotation is very nearly uniform, while the revolution is in accordance with Kepler's second law, the moon seems to rock a little and so permits us to see now a small area on the right and now a small area on the left that are ordinarily invisible. This effect, the *geometrical libration* of the moon, is the last of Galileo's discoveries.

Galileo's application of the telescope to astronomy was the occasion of truly epoch-making revelations. Nevertheless, they do not constitute his principal claims to the gratitude of astronomers. Most of these discoveries would probably have been made soon after by others, though few would have seen so readily or explained so clearly their philosophical import. Of greater consequence than these discoveries was the part he played in establishing the true system of the world, a far more important one than that played by Copernicus himself; and of still greater consequence was his formulation and experimental proof of the laws of motion, a work that prepared the way for Newton and for the discovery of the law of gravitation.

Isaac Newton was born in 1642, the year of Galileo's death. He was the posthumous and only child of a farmer at Woolsthorpe, a small village about one hundred miles north of London. Like all his great predecessors in modern astronomy (Copernicus, Tycho, Kepler, and Galileo) he had the advantage of university training, graduating from Trinity Col-

lege, Cambridge, in 1665 and remaining connected with that institution until 1701. During this period he prepared and published (1687) his great work on the *Philosophiæ Naturalis Principia Mathematica,* commonly referred to as the *Principia.* In 1699 he was appointed Master of the Mint, a responsible public office that he held until his death in 1727 in his eighty-fifth year. To him more than to most was given that quiet and uneventful career that great philosophers need and deserve.

In 1666 Newton was driven from Cambridge by the plague that had spread from London, and he spent some months at his mother's home at Woolsthorpe. There he began his researches into the nature of gravitation. It must not be supposed that Newton discovered the existence of gravitation. Many writers refer to such a force and even the Greeks had some vague notions about it. In Newton's own day and especially by his own countrymen, we find many references to it. It was Newton who found out how gravitation varies with distance and who showed that the familiar phenomena of falling bodies at the surface of the earth were merely manifestations of a force that pervades the universe.

Wherever we go upon the earth, even to the tops of the highest mountains, all objects tend towards the center of the earth with apparently undiminished vigor. How far up does this tendency go? Can it reach as far as the moon? These were the questions that Newton asked and answered. Galileo had already shown that uniform motion is as natural as rest, and that deviation from such motion implies a force. If then the moon were relieved of all forces it would leave its orbit and move along a tangent. Consequently, if the earth attracts the moon, then what that attraction really does is to draw the moon out of the tangent into the orbit. As the period and distance of the moon are known it is easy to compute how much the moon falls away from the tangent in one second. Comparing this with the speed of a falling body in our laboratories,

Newton found the ratio of these two speeds to be about as one to 3600. As the moon is sixty times as far from the center of the earth as we are, this implies a force that decreases with the square of the distance.

Is there a force residing in the sun, keeping the planets in their orbits, similar to the one that keeps the moon revolving around the earth? The answer to this question is to be found in Kepler's laws. Newton showed that the second law (equal areas in equal times) implies a force directed towards the sun; that the first law (that orbits are ellipses with the sun at one focus) is a consequence of the inverse-square law of attraction; and finally that if the same law holds in going from planet to planet, then the periods and distances of the planets must be related as required by Kepler's third law, modified a little to allow for the masses of the planets, which are not quite negligible compared with that of the sun, as Kepler had tacitly assumed. Newton was now able to announce the law of gravitation in its most general form: *every particle of matter in the universe attracts every other particle with a force that varies inversely as the square of their distance apart, and directly as the masses of the two particles.*

A good deal of the progress of astronomy since this law was announced has been concerned with its application to the solar system in all its ramifications. Newton himself pointed out many of its chief consequences. He found in it the explanation of the tides. The moon attracts a particle at the center of the earth less than she does the ocean on the nearer side, and more than the ocean on the farther side; and so the water bulges away from the center at both these points. As the earth revolves on its axis every place is thus brought twice daily into regions where the water is high, and twice daily where it is low. The sun raises two similar tides, but as he is so much farther away than the moon, his tides are less than half as great in spite of his much greater mass.

It had already been indicated by pendulum experiments that the earth deviates slightly from a truly spherical form, modern measurements showing that a diameter through the equator exceeds that through the pole by about one part in three hundred. Newton pointed out that this form is a consequence of the earth's daily rotation around the polar axis; and he went on to show that the precession of the equinoxes, discovered so many centuries earlier by Hipparchus, was caused by the attraction of the moon and the sun for this additional matter at the earth's equator.

Up to the second half of the seventeenth century astronomy was followed by a few votaries, for the most part widely separated from each other. It is a striking fact, for example, that of the great modern names we have thus far dwelt upon, no two belong to men of the same nationality, and none of them can be said to have founded a school. Now, however, we enter a period when science calls for and attracts many devotees. National academies are created for the promotion of research, regular media are provided for the publication of results, great observatories like Greenwich and Paris are founded and bring together groups of men who are working on similar problems.

Thus far we have been able to adhere to the chronological order of events, for the simple reason that astronomy has been concerned with a single great problem, the plan of the solar system. But hereafter the subject becomes more varied, and in a brief account all that we can hope to do is to reproduce the spirit of astronomical progress. What follows is a set of selections from the history of the subject, made less with a view to their relative importance than because they can be described without recourse to technical details. That some great names and some great deeds are omitted is inevitable.

The application of Newton's law throughout the solar system is a task of incredible difficulty, one that has taxed the

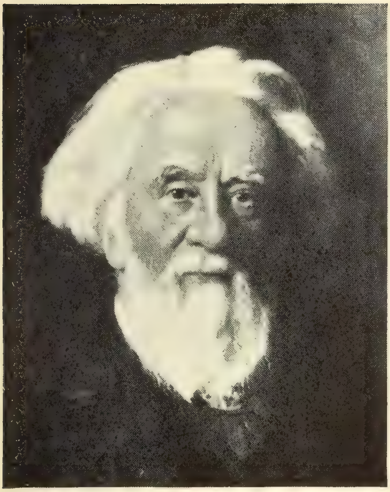
powers of such giants as Laplace, Lagrange, Euler, Adams, Delaunay, Hill, Newcomb, and Poincaré. It is of the greatest philosophical importance that this task be completed, for in hardly any other way can we hope to learn what forces other than the gravitation of known bodies are abroad in the universe. Already this method of exclusion has led to important results. It was in this way that Neptune, the outermost planet, was discovered. In 1783 William Herschel, then a professional musician and an amateur astronomer at Bath, England, had discovered Uranus, the first addition to the sun's family of planets since remote antiquity. It was soon learned that after allowing for the attractions of all known bodies the computed path of Uranus did not conform with observation. Leverrier in France and Adams in England independently concluded from these differences that still another planet must exist beyond Uranus, and they were able to say where to look for it. And a new planet, Neptune, was found by Galle in 1846 on the first night that he searched.

The motion of the moon furnishes another example of somewhat the same kind. After allowing for the action of all known bodies, two outstanding effects remain; one of these is the existence of the so-called *fluctuations,* apparently erratic in character, for which no explanation is as yet forthcoming. The other is an exceedingly small speeding up of her rate of revolution. In recent months it has been shown that this effect is only apparent and is due to the fact that our timepiece (the earth) is at fault, the friction of the tides on the floors of shallow seas being sufficiently great to slow up the earth's rotation a trifle and thus make the moon appear to run fast.

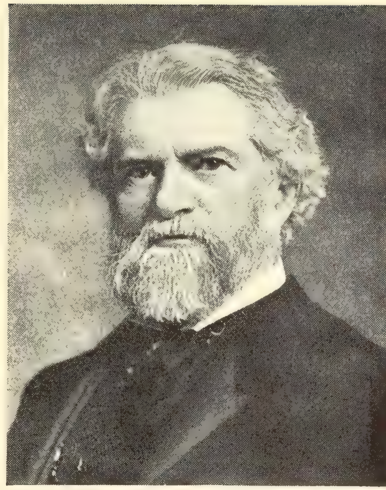
Still a third effect of the same kind is fresh in our minds. Gravitation alone does not explain very satisfactorily the motion of Mercury, a very slow revolution of the whole orbit (at the rate of 40″ a century) remaining to be accounted for. Einstein's new theory of relativity does this very well, and that

theory has received another striking confirmation in the amount by which light is deflected in passing close to the sun, as shown by measurements made during the 1919 eclipse. It is too early to pronounce judgment on the validity of this new theory. Experiments that should enable us to decide are in progress and their results will soon be available. If Einstein's theory should be corroborated, then it will be necessary to regard Newton's law as being not quite rigorous but as requiring a small correction.

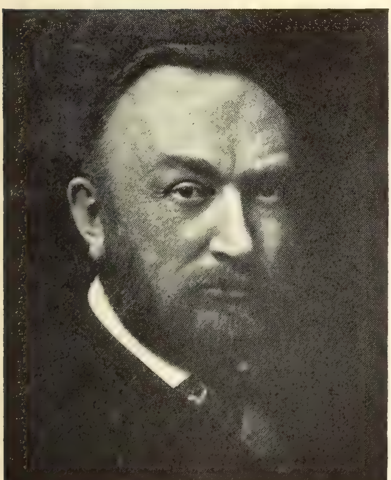
Newton's genius shone with so much brilliance that our eyes are blinded to the lesser lights of his time, lights that would have been far more conspicuous if that great luminary had not been above the horizon. This is particularly true of Edmund Halley (1656 to 1742), a close friend of Newton and his junior by fourteen years. It is doubtful whether Newton could have been induced to prepare the *Principia* without Halley's encouragement and persuasion, and Halley personally bore the expense of printing this work. This man's activities covered an extraordinarily wide field. He made important contributions to terrestrial magnetism, to the explanation of aurora, and to the theory of life insurance; he first predicted the return of a comet (the one that has since borne his name), suggested the first accurate method for determining the distance of the sun, compiled the first catalog of southern stars, and discovered two important perturbations in the motions of the planets and of the moon. But the discovery that we wish to speak of in more detail relates to the *proper motions* of stars, their changes of position with respect to each other. Twenty centuries earlier Hipparchus had constructed a catalog of stars, setting down their positions as accurately as his instruments permitted. Halley in 1718 compared these positions with those made in his own time, and detected motions in several of them. This was the first indication of how important it is to observe the places of stars, and may be con-



Sir William Huggins.



Simon Newcomb.



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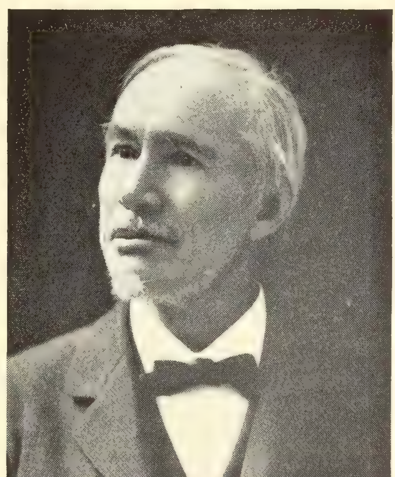


George William Hill.

sidered the beginning of a research which is by no means complete even now, one that has taxed the industry, patience, and ingenuity of all succeeding generations of astronomers. The idea that these motions may be in part only apparent and due to a motion of the sun among the stars occurred to Bradley of Oxford in 1748 and to Mayer of Göttingen in 1760. But the first one to show that this is so from the numerical data was William Herschel (1738 to 1822), who in his first research used only seven stars. He found that their motions indicated that the sun (carrying all his planets with him) is moving swiftly towards the constellation Hercules. This general conclusion has been verified by many later researches dealing with many thousands of stars. According to this view all the stars, including our sun, are moving hither and yon in haphazard directions. Twenty years ago a new phase of this subject was revealed by Kobold of Kiel and especially by Kapteyn of Holland. The latter found that after allowing for the motion of the sun, the movements of the stars are not quite haphazard, but that they could be accounted for by supposing that there are two groups of stars, within each of which the motions are haphazard, but the two are moving through each other. This is Kapteyn's own interpretation; a very different one was suggested by Schwarzschild of Potsdam (1873 to 1916), who supposes that there is only one group of stars, some of which will be found moving in any specified motion, but as a whole showing preference to motions that are parallel to a certain line. These two interpretations sound radically different, but they lead to nearly the same statistical results, at any rate so nearly the same that we cannot distinguish between them with our present knowledge of proper motions. Perhaps there is no other problem with which astronomers have to deal that is philosophically more important than this, for its solution will tell us whether the so-called universe of stars is really a universe, or whether it is dual in character and possibly in

origin. Of somewhat similar import has been the detection of what are known as *moving clusters,* the best example of which is the one found by Boss (1846 to 1912) of Albany. It covers a considerable part of the constellation Taurus. Here there are about fifty bright stars whose motions are very closely parallel to each other. Still another development along the same lines is the detection of distant companions to bright stars, sharing the proper motions of the latter in both amount and direction, but very much too distant to be appreciably affected by their attraction. Thus the bright double star *Alpha Centauri* has a companion no less than 2° away that shares its exceptionally large proper motion of 4″ a year.

Such problems as these account for and justify the extraordinary amount of labor that has been put into the determination of star places and therefore of their motions. Many catalogs containing accurate positions of thousands of stars have been issued in the past century and a half, beginning with that of Bradley in 1755. Altogether more than one million observations of this kind have been published, all made by the laborious method of observing directly with the eye by means of meridian circles. About thirty-five years ago a very ambitious plan for the location of several million stars with the aid of photography was undertaken by international coöperation. This work, the *Astrographic Catalog,* was badly interrupted by the great war, and doubtless many years will elapse before it can be completed.

The determination of the distances of stars has engaged the attention of astronomers in every age. It has not only been of prime importance in itself, but has yielded unusually interesting by-products. For one thing, no other problem has so constantly spurred astronomers to improve their methods of observing. We have seen that Tycho found stellar distances to be so great that their parallactic shifts were insensible to his unprecedentedly accurate instruments. He would doubtless

have been surprised to learn that had his instruments been one hundred times as accurate they could still not have revealed these shifts. But long before astronomers were in possession of instruments of this degree of accuracy they knew in a general way how distant the stars must be. This knowledge came with the realization that the sun is only a star; considerations of the relative brightness of the sun and stars led at once to a proper conception of their distances. Attempts to measure these distances directly followed almost every substantial improvement in methods of observing. James Bradley (1692-1762), easily the most accurate observer up to his time, made observations for this purpose, but instead of yielding a parallactic displacement the observations led to the discovery of the *aberration* of light. This is an effect caused by the combination of the earth's motion around the sun, carrying the observer along at the rate of nineteen miles a second, and of the speed of the light from the star, about ten thousand times as great. As a result all stars in the sky are apparently displaced by amounts up to 20″. The detection of a measurable parallax would have afforded direct observational evidence of the motion of the earth around the sun and therefore of the truth of the Copernican system, though, of course, proof of this kind was no longer needed. Curiously enough, this unexpected detection of aberration furnished equally convincing proof to the same effect, since its existence depends as much upon the motion of the earth as does that of stellar parallax.

Galileo had suggested that the relative positions of a bright and a faint star close together in the same telescopic field might yield evidence of parallax. William Herschel, provided with a reflecting telescope capable of sustaining unusually high magnifying powers, put this suggestion into practice. Like Bradley he failed, and like Bradley he made instead a wholly unexpected discovery of first importance. He had selected pairs of stars under the assumption that the brighter star of the two

was nearer than the fainter; but in some of these cases he found that the two were slowly revolving around each other; or in other words, they formed *binary* systems, held together by their mutual attraction. Subsequent study of such pairs, of which thousands are now known, shows that Newton's law of gravitation applies to them, and thus extends this law beyond the confines of the solar system.

The invention by Dollond and Bouguer of a new kind of measuring instrument, the *heliometer,* its improvement by Fraunhofer, and above all its skillful use by Bessel of Königsberg in 1838, yielded the first reliable measurement of a parallax. The method employed is necessarily a very laborious one, so that by the end of the nineteenth century trustworthy distances for only thirty or forty stars had been accumulated. Since then photography with telescopes of great focal length has increased the accuracy of these determinations and has greatly decreased the labor of making them. This work now forms an important part of the observing programs with seven or eight of the most powerful telescopes and has already yielded accurate parallaxes of fifteen hundred stars. Very recently a spectroscopic method for determining stellar distances has been developed by Adams and Kohlschütter at Mount Wilson Observatory in California. Stars appear to us to be of different magnitude or brightness partly because they are at various distances from us, and partly because their actual or *absolute* magnitudes differ enormously, some stars sending out a million times as much light as others. If we had any way of estimating this absolute magnitude we could say how far any particular star must be away in order that its light should reach us with the intensity that it appears to have. The new method furnishes a means for making this estimate. It is based upon the fact that the intensities of certain lines in stellar spectra are found to vary with absolute brightness; we can now reverse the process and infer the absolute brightness from a study of

the relative intensities of these critical lines. This method proves to be more accurate than any other in the great majority of cases, and is also very expeditious, the distances of nearly two thousand stars having already been ascertained in this way.

This latest triumph of the spectroscope is one of a long series. Through the labors of Huggins, Lockyer, Pickering, Vogel, Campbell, and many others, we can now tell from a study of the spectrum of a celestial object what known elements enter into its composition; whether it is gaseous or stellar; if the latter, whether it is single or double, and a surprising number turn out to be double; the rate at which it is approaching or receding from the solar system; its approximate temperature; and now finally, its distance.

The labors of astronomers are for the most part bent to the extension of our knowledge of nature, necessarily with little thought as to the application of any such knowledge to everyday life. There is one noteworthy exception to this: the study of the sun not only possesses all the allurements of so-called pure science, but those who devote themselves to it have the added satisfaction of knowing that such work will in all probability eventually lead to results of material importance. Radiations from the sun of various kinds are the source of all forms of energy available to us and are essential to the maintenance of life on this planet. Additional knowledge concerning the nature of these radiations will doubtless materially enhance the general welfare of mankind. Essential crops throughout vast areas are occasionally afflicted with lean years that bring misery to millions of men. It is not too much to hope that the time will come when such lean years will be predicted and thus make it possible to forestall much of the suffering they entail.

The study of the sun progressed very slowly at first. The detection of sunspots early in the seventeenth century remained

an isolated fact for more than two centuries. By that time the spectroscope was turned to the sun and some of the innumerable dark lines in its spectrum were mapped by Fraunhofer. But it was not until 1859 that Kirchhoff and Bunsen found the key to these lines; they showed that most of them are caused by absorption in the very shallow and comparatively cool atmosphere of the sun. Each element has its characteristic lines which appear wherever the absorption takes place, whether in the laboratory, in the sun, or elsewhere. Here then is a means of analyzing the sun in the chemist's sense. It is found that almost all common elements that we find at the surface of the earth are also plentiful in the sun. But more than half the lines in the sun have not yet been identified with known elements. They offer a continual challenge and doubtless will lead to the detection of new substances in the earth, as indeed they have already done.

For two centuries after the discovery of sunspots, no one thought it worth while to observe these evanescent objects systematically, any more than today we should deem it profitable to record in detail the number and size of the clouds in our own atmosphere. But in 1826 Heinrich Schwabe of Dessau began to observe them on every clear day with a small telescope, and continued to do so for nearly half a century. He found that in some years hardly a spot was to be seen, while in others the sun's face always showed a number of them. This was the discovery of the sunspot cycle, or period of eleven years. The same cycle has been found to apply to phenomena that have apparently no connection with sunspots. For example, the magnetic needle shows a daily swing about its average position; Lamont found in 1851 that in the years when sunspots are plentiful this swing is more pronounced than in other years. Again, aurora are rare when sunspots are rare. The corona, that pale light visible around the sun only during a total eclipse, changes its shape and general ap-

pearance in the same eleven-year cycle, and so on. The nature of the connections between these various phenomena is still unknown; probably no one of them is the direct consequence of any other, but all are effects of the same underlying cause.

Until lately practically nothing was known concerning the nature of sunspots; we are still far from anything like definite knowledge, but at least a clue has been found. A gas heated to incandescence gives a spectrum made up of sharp bright lines. Twenty-five years ago Zeeman found that if the light of this gas is made to pass through a strong magnetic field, these lines are now split into two or three components. The spectrum of sunspots differs in a similar way from that of the general surface of the sun, and Hale at the Mount Wilson Observatory has proved that the cause of this difference is the same, and that sunspots are the seats of strong magnetic fields. Furthermore, the spots are found to occur in pairs with opposite kinds of magnetism, as though the ends of an enormous iron magnet were protruding from the interior of the sun to its surface. Hale has likewise shown that the whole sun may be regarded as a magnet, being in that respect like the earth, so that a balanced magnetic needle (or compass) on the sun would indicate the north direction just as it does here.

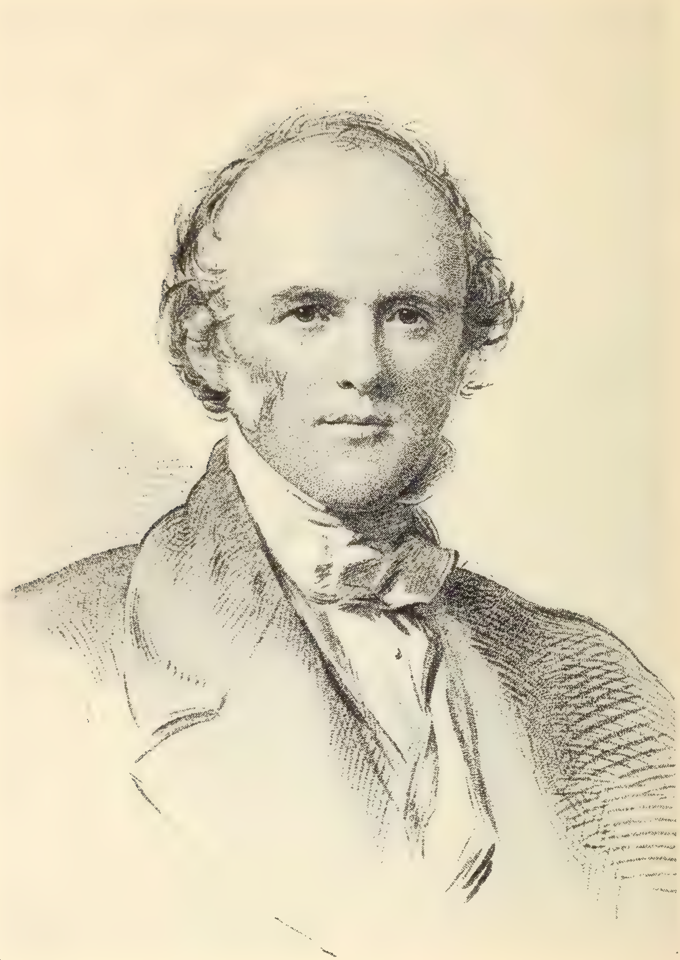
From observations of sunspots and otherwise, we can determine the rate at which the sun revolves on its axis. In 1859 Carrington of Redhill found that no one rate applies, but that the farther we go from the sun's equator the more slowly does the surface go around. No convincing explanation for this kind of rotation has as yet been advanced, nor has a cause been assigned to another curious effect discovered by Carrington. When sunspots begin to appear after the lull called *sunspot minimum,* they come in zones comparatively far from the equator, north and south. As they become more and more

plentiful their average position is nearer and nearer to the equator.

Some stars do not always radiate the same amount of light and heat, and as our measurements of stellar brightness improve in accuracy, more and more stars are found to be thus variable. The question arises whether our star, the sun, may not be one of this number. Recent researches indicate that this may be the case, the heat of the sun as measured at mountain observatories varying as much as 10 per cent. It is not certain that this change really occurs in the sun. It may be that our atmosphere sometimes blocks more of the sun's heat than at other times. If this is so, the effect must be world-wide, since observations made on different continents show the same trend.

The early history of astronomy is closely interwoven with that of mathematics and its recent history with that of physics. The astronomer has borrowed almost all his tools from the physicist; the prism, the grating, the photoelectric cell, the interferometer, the photographic plate, even the telescope itself, were all used in the laboratory before they were applied to the sky. But it would be a mistake to regard astronomy as being a branch of physics or of any other science. Astronomy has a distinguishing and essential characteristic that it is well to emphasize if we wish to understand the spirit of its history. Many of the facts of the science can be brought out only by observing changes that are going on in the sky, and many of these changes are exasperatingly slow. Some are rapid enough to be detected or well measured in a century or less, while others require thousands of years to run their course. Some of the greatest names in the history of the science are those of men who foresaw the possibility of such changes and who set about making as accurate observations as they could, knowing

well that they could not live to see these observations fulfill their purpose, but conscious of the value that their work would take on after the lapse of years. It is this characteristic of his work that is at once the despair and the inspiration of the astronomer. He often has occasion to envy the physicist and the chemist who are able to complete their own experiments. On the other hand, his work is not so easily superseded as theirs; for although it will happen to him as often as to anyone else that later improvements will make his own observations relatively inaccurate, these observations may still continue to be useful because they were made early, the element that preserves them from decay being their epoch. And as a corollary to this, the history of astronomy contains (and will continue to contain) many examples of men who have been able to make advances because they were acquainted with this history and have known where to look and what to look for in the records.



SIR CHARLES LYELL

CHAPTER V
GEOLOGY

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THE history of geology is essentially the history of the intelligent observation of rocks, fossils, and land forms. Progress is marked by progressive increase in exactness and completeness of observation. In an atmosphere saturated with tradition and personal bias the making of observations and the interpretation of observations present but a sickly growth; and when the intellectual environment includes authority and a complete outfit of supernatural causes, growth is stopped entirely. This may in part account for the interesting fact that philosophy and literature rather than observational science represent the intellectual efforts of the ancients. Poetry and musings about the nature of things require no special technique, no collections of materials for comparison. A gifted mind is the essential equipment; and such minds may appear anywhere and at any time. But the development of natural science involves critical observation of a variety of things from many places, the interchange of ideas among many workers, the making of hypotheses, the formulation and selection of method, and the invention of apparatus. It is natural that this group of requirements should come together slowly.

In no real sense can the obvious geological truths irregularly interwoven in the interesting fabric of myth and fact which constitutes Greek, Arabic, Indian, and Chinese thoughts on

nature be considered the beginnings of geology. The traditions of the Mediterranean peoples, of the Hebrews, Babylonians, and Hindus, are rich in speculation and in the making of hypotheses regarding earth origin, but poor in logical deduction from exact observation. They show little interest in the earth itself and no inkling that the history of the earth is to be deciphered by means of fossils, knowledge of the earth's crust, and the action of rivers and waves. The test is the extent to which the contributions of the ancients were utilized as stepping stones. In geology progress has been attained without regard to or even in ignorance of observation and theories recorded before the late Middle Ages. Cuvier established paleontology without reference to the teachings of previous times and even in ignorance of the work of his contemporaries, and Darwin acknowledged his indebtedness to Lamarck, not to Aristotle, whose theory of evolution lacked little of being complete. Likewise structural geology, stratigraphy, and physiography have grown up without assistance from classical and Middle Age scholars. The fifteenth century student of earth science enjoyed a surprisingly meager heritage from classical and early Christian days. In the sixteenth century Leonardo da Vinci stands alone. During the seventeenth century many sciences made great strides forward; new facts were unearthed and methods established. Physics received the contributions of Galileo, Kepler, Newton, Torricelli, Guericke, Boyle, Huygens, Hooke. Astronomy, already far advanced, was revolutionized by the development of the telescope, and biology by the microscope. Chemistry found a place apart from alchemy and medicine. In geology, on the other hand, the seventeenth century scholar was groping in darkness scarcely less dense than that surrounding his predecessors of the sixteenth and fifteenth centuries.

Towards the close of the eighteenth century many of the

facts and principles and methods which constitute geology were assembled but geology as taught today is essentially a nineteenth century product, to which many of the most significant contributions have been made by scholars of the present generation.

The subject-matter of geology is so varied and the introduction of new views so irregularly placed in time that no chronologic sequence appears in the growth of the science as a whole. Development may best be shown by tracing the growth of certain fundamental ideas: the origin of the earth; the meaning of rocks, mountains, surface features, and fossils; and the geologic time scale.

Origin of the Earth

From direct observation geology knows nothing of the original earth; no part of its first formed surface has been seen or is likely ever to be seen. The oldest rocks known have doubtless been derived from rocks yet older, and the oldest fossil undoubtedly descended from a long line of still older organisms. The evolution of the physical earth and of life clearly point to a period charged with dynamic and vital forces long antedating the most ancient legible records.

It must be admitted that so far little clear light has been thrown on the origin and primeval condition of the earth. For the geologist there is little choice between the childlike myths of the Eskimos, Bushmen, and Micronesians, the grand poetic conceptions of the Hindus, Babylonians, and Hebrews, and the pseudoscientific teachings of the Greeks and medieval churchmen.

An advance is recorded during the seventeenth century in the contributions of Descartes (1596-1650) and Leibnitz (1646-1716), who traced the development of the earth from a disordered mass of glowing material to a smooth, solid globe, the exterior of which had cooled. These ideas were ex-

panded and built into a consistent theory through the labors of Kant (1755) and especially of Laplace (1796),[1] whose views of earth origin received well-nigh universal acceptance during the nineteenth century. In essence the nebular hypothesis of Laplace assumes the existence of highly heated gaseous nebulæ slowly rotating about a central mass which eventually became the sun. As this nebulous material rotated, cooled, and contracted, rings of matter were detached one after another, furnishing the stuff for planets and satellites. One of these rings, gathered into a spheroid, became the earth. The original earth, therefore, was a luminous star surrounded with a heavy vaporous atmosphere. The ball passed from a gaseous to a liquid state and developed a wrinkled crust of igneous rock like granite. Later the atmosphere gave rise to oceans and streams, agents for the production of sedimentary rock.

The nebular hypothesis is the crowning achievement in cosmical geology up to the end of the nineteenth century, but its value lies not so much in its inherent probability as in the absence of a better theory. It violates the principles of thermodynamics and of celestial mechanics and is out of accord with the present knowledge of nebulæ, planets, and satellites. Furthermore, the theory demands progressive cooling of the earth, and an arrangement of rock masses amply disproved by geological evidence. Without radical reconstruction, the nebular hypothesis can no longer serve as a reasonable theory of earth origin.

The underlying conceptions of the nebular hypothesis are: first, the condensation of diffuse matter under the action of gravity, and second, nebulæ distended by heat and revolving as a unit mass. But the researches in astronomy and physics during the past quarter-century have accumulated evidence to show that disruption and repulsion, not attraction, are the dominant forces in the stellar universe. The tails of comets

[1] Laplace, P. S., Exposition du système du monde, Paris, 1796 and 1824.

turned away from the sun, streamers thrown from the sun itself, and the shape of certain star clusters and nebulæ point to prodigious repelling forces within the luminous bodies making up the universe. On such evidence the planetesimal hypothesis of Chamberlin and Moulton is founded.[2] Under this theory the earth was once a spiral nebula composed of matter "thrown out" by some ancestral sun. The scattered particles, or planetesimals, of the parent nebula were drawn into nuclei which became part of the planetary system. At this stage the cosmic history of the earth passes into the geological history. The original earth is conceived as a ball 2000 to 3000 miles in diameter, which grew to its present size by the addition of more planetesimals. The internal heat of the earth comes from self-condensation and progressive close-packing of its constituent planetesimals. Under this theory volcanism was active long before the earth attained its present size, and an atmosphere appeared as soon as the earth possessed sufficient gravitative power to retain it. When the atmosphere became saturated with aqueous vapor, water was formed and occupied depressions in the earth's uneven surface.

The truth of the planetesimal hypothesis remains to be separated from its errors by a long period of testing and developing. Its value lies in the fact that it explains a great number of geological observations and suggests lines for future investigation.

Meaning of Rocks

The origin of the earth and the history of life on this planet are involved in religious and philosophic views and therefore precede in point of time the study of the materials of which the earth is composed. At the beginning of the nineteenth century some progress had been made in the knowledge of minerals,[3]

[2] Chamberlin, T. C., The Origin of the Earth, 1916.

[3] Ford, W. E., The Growth of Mineralogy from 1818 to 1918, in A Century of Science in America, E. S. Dana, Editor, 1918.

but so little was known of the composition and texture of rocks that masses of igneous origin were confused with strata laid down by water or by wind, and the existence of vast exposures of metamorphic rocks was not recognized. The distinction between a rock and a geological formation or group of strata had not been fully established, and many fine-grained rocks were classed as minerals. As late as 1837 the Munich chemist, Johann Fuchs, contended strenuously for the view that mica schist, granite, and porphyry were the results of the consolidation of a watery paste. Only within the past fifty years has the systematic investigation of rocks—their composition, relations, and origins—reached a stage that justified the recognition of a distinct branch of geologic science. Since the importance of its contributions has been demonstrated, the study of rocks has experienced two somewhat distinct but logical periods of development. *Petrography,* the description of rocks, is a necessary forerunner to *petrology,* researches in the origin and broader relations of rocks.[4]

The stages of advancement in petrography may be traced by noting the systems of classifications in vogue at different periods, for classification involves the application of all known facts about all known kinds of rocks and also a consideration of existing theories and assumptions. The classifications of rocks based on hardness, specific gravity, and geographical location, are obviously superficial and one may dismiss as a humorous but futile notion the dictum of Jameson that there is but one species in mineralogy, namely, the globe, and the wordy argument of Pinkerton (1811) that no *species* of minerals exist, for no mineral has the capacity to reproduce its kind. It is easy to understand, however, that students of rocks should have placed different emphasis on chemical composi-

[4] Pirsson, L. V., the Rise of Petrology as a Science, *ibid.*
Cross, Whitman, The Development of Systematic Petrography in the Nineteenth Century, Jour. Geology, 10, 1902.

tion, texture, mineralogical composition, age, mode of occurrence, and origin, as criteria, and should be of different minds regarding the desirability of a "natural classification" as opposed to an artificial one.

Early in the eighteenth century contributions to the knowledge of rocks were made by the few men who resisted the temptation to speculate and to dogmatize about things in general, and who confined their attention to a particular topic or a particular locality. Carolus Linnæus (1707-1778) extended his *Systema Naturæ* to include the inorganic kingdom, which he divided into rocks, minerals, and fossils. To each of these subdivisions was assigned an incongruous group of materials. As remarked by Cross, the most visible effect of this pioneer attempt to force inorganic substances into the scheme of species and genera provided for plants and animals was to furnish a theme for controversial debates and arguments for a century to come.

The outstanding figure among students of rocks of the eighteenth and early nineteenth centuries is Abraham Gottlob Werner (1749-1817), professor of mineralogy at Freiberg, whose enthusiasm, eloquence, skill in teaching, and clear methodical presentation attracted learners from all parts of Europe. Werner's views of rock genesis and of geological processes were antiquated even for his time, but his painstaking systematic examination of rocks led to a classification based on mineral composition (1786)—a feature common to modern schemes. He distinguished "simple" from "compound" rocks, recognized that some minerals were "essential" components of rocks and others "incidental" or "accessory," and clarified the subject by drawing the distinction between rock masses or strata (formations) and the rocks composing them, thus laying the foundations of modern descriptive petrography. During the first two decades of the nineteenth century, the knowledge of rocks as summarized in systems of classifications was

carried as far as possible under the Wernerian scheme by Haüy (1801), Brongniart (1813), Cordier (1815), and their contemporaries, who relied upon mineralogical composition and structure to indicate relationship to the exclusion of age, origin, and mode of occurrence.

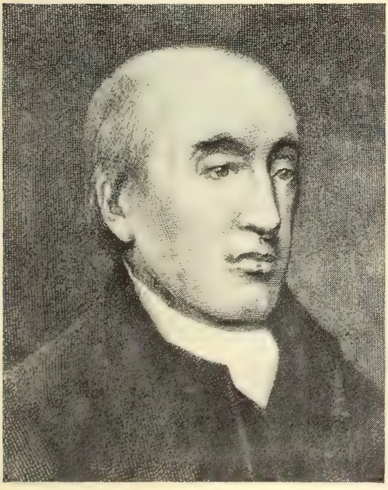
But even during this period the problem of rock origin was prominently in mind. Were all rocks deposited by the ocean as chemical precipitates, as taught by Werner, or do deep-seated igneous rocks and lavas and sedimentary rocks indicate three modes of origin, as taught by Hutton? Do the different kinds of rocks represent merely different ages of accumulation or are granite and sandstone made in all ages, even today? Are gneiss and schist original igneous rocks or altered sedimentary rocks? As if by common consent, the origin of the lava, basalt, was taken as a test case, and geologists, chemists, physicists, and even literary men and politicians, divided into two camps —the Neptunists, who contended that basalt is deposited from sea water, were vigorously opposed by the Plutonists, who believed in an igneous origin. Peace was declared in favor of the Plutonists soon after it was agreed that field observations were better weapons than arguments concocted in the library.

A distinct advance in the knowledge of rocks is recorded by two publications in the third decade of the nineteenth century.[5] Von Leonhard's *Characteristics of Rocks* (1823) is listed by Cross as "the first fairly consistent treatise on rocks" and its author as "unquestionably the foremost petrographer of his day, sharing with Alexandre Brongniart the honor of placing the classification of rocks on a firm basis as a systematic science." Through the work of these able minds the confusion heretofore existing between minerals, rocks, and assemblages or groups of rocks (terranes and formations) was eliminated;

[5] Von Leonhard, K. C., Charakteristik der Felsarten, 1823.
Brongniart, Alexandre, Classification et caractères minéralogiques des roches homogènes et hétérogènes, Paris, 1827.

Abraham Gottlob Werner.

William Smith.



James Hutton.

Baron Cuvier.

the study of rocks as rocks (petrography and petrology) was shown to be a branch of learning with methods and purposes different from the study of strata and masses composed of rocks (stratigraphy); and the biological scheme of genera and species was discarded as inapplicable. These workers showed that structure, as well as mineralogical composition, is a significant feature, and Brongniart suggests that geological origin may have value as a principle of classification. Both authors state with refreshing candor that fuller knowledge will show that many rocks have been given inappropriate places in the scheme of classification. To his major divisions, (1) heterogeneous rocks, (2) homogeneous rocks, (3) fragmental rocks, (4) loose rocks, Von Leonhard added a group, "rocks apparently homogeneous," to care for serpentine, pitchstone, and certain schists whose constituents were not visible to the unaided eye but which were not minerals. Brongniart subdivided "homogeneous rocks" into those with distinct known mineral species and those whose extremely fine grain precluded the recognition of constituents.

A new mode of treatment was introduced into the science of rocks by Carl Friedrich Naumann (1850 and 1858).[6] Under the name *petrography* he defined the scope of the science of rocks as a branch of geology (or *geognosie* as the term was then used) which could be studied from six standpoints: the constituents of rocks, the texture and structure of rocks, manner of occurrence, systematic description, genesis of rocks, and alteration of rocks. He introduced the classification: (1) crystalline rocks, (2) clastic rocks, (3) rocks neither crystalline nor clastic.

Von Cotta's contribution[7] (1855 and 1862) was the emphasis placed on geological mode of origin and the clear ex-

[6] Naumann, C. F., Lehrbuch der Geognosie, 1850.

[7] Cotta, Bernhardt von, Rocks Classified and Described; a Treatise on Lithology (trans. P. H. Lawrence, 1866).

pression of the modern view that molten material poured from volcanoes and molten material formed deep within the crust of the earth may be crystallized into rock during any geological epoch and are not therefore indicative of age.

Frederick Senft (1857), probably impressed by the difficulty of determining the characteristics of dense rocks, minimized the value of mineralogical composition, texture, and structure as interpretative guides and developed an elaborate and highly artificial scheme based on chemical composition. But the master mind of the group whose attention was directed to the chemical relationship of rocks was Justus Roth. From a careful study of nearly 1000 analyses he reached the conclusion (1861) that rocks cannot be represented by chemical formulæ which coincide with mineralogical composition, and that the application of the chemical factor as a criterion in classification serves to separate rocks otherwise closely related. As a substitute he proposed that igneous rocks be grouped with reference to the abundance and kind of feldspar crystals contained within them.

An opposite conclusion was reached by Sheerer (1864), who expressed the belief that igneous rocks could be satisfactorily grouped in nine chemical types.

Zirkel's *Lehrbuch der Petrographie* (1866) and the philosophical discussions of von Richthofen (1868) are substantially restatements of earlier views, but are worthy of study as expressions of the usages and beliefs of the time and as the culmination of efforts to describe and to interpret rocks on the basis of superficial characteristics and approximate chemical analyses.

By 1850 the possibilities of increase of knowledge through the study of rocks appeared to have been exhausted; no further steps of advance seemed possible, for the components of fine-grained rocks, lavas, and schists were beyond the reach of observation and there appeared to be no satisfactory means of

distinguishing the varieties of feldspars, the most abundant ingredient in the commonest rocks. Petrography had come to a blank wall. Further research involved the discovery of some method for more complete and exact observation. The need was met by the introduction of the compound polarizing microscope, which brings to view and differentiates minerals even in apparently homogeneous rocks. The development of this instrument and of the means of preparing rocks for study marked the beginning of the golden age of descriptive petrography, the last quarter of the nineteenth century. The way had been blazed by Professor Nicol, the Scotch geologist, who invented the Nicol prism for polarizing light, attached it to a microscope, and devised a method for preparing thin sections of fossil wood (1828). The success of this method led Ehrenberg to the epoch-making discovery that chalk and marls and some limestones were composed of skeletons of organisms. Sorby (1850) used this method for determining the composition of sandstone and discussed its value for the study of igneous rocks. But to make a chip of hard rock sufficiently thin to be transparent seemed a hopeless task. It is a triumph of technical skill to cut from a black dense rock a section 1/1000 of an inch thick through which print may be read and which reveals to the microscope the minutest structures. The seemingly impossible has been accomplished and the modern geologist is placed in the position of the biologist with respect to the examination of microscopic objects of natural history. This method of research under the lead of Zirkel and Rosenbusch in Germany, Michel-Lévy, Barrios, and Lacroix in France, Bonney, Judd, and Rutley in England, E. S. Dana, G. H. Williams, and Iddings in America, promised so much that it soon enlisted an army of workers who added enormously to the knowledge of rocks and of the minerals composing them. During the closing years of the nineteenth century, microscopic

description of rocks appeared to be the chief aim of petrographers.

About the beginning of the present century *petrography* became *petrology;* the science of the exhaustive description of rocks became the science of relations and meaning of rocks. The genesis of rocks and the factors that have brought about their geographic distribution and produced the hundreds of varieties are topics of interest to a modern student of petrology. The goal is in sight, but the best means of reaching the goal is not apparent. As in other lines of research, progress depends upon choice of method. Reliance on the petrographic microscope has revealed a new world to geologists, but it has obvious limitations. It is an instrument for collecting data, for refined and accurate description rather than for determining origins, and after all known rocks and rock-making minerals have been studied this method has served its main purpose. This stage nearly has been reached. Twenty years ago most minerals, certainly all those of wide distribution, had been exhaustively studied and igneous rocks by the thousands had been minutely described and built into schemes of classification. Many sedimentary rocks and schists and gneisses also have been added to the list. Progress has been attained by the development of chemical methods of research in rock origins and rock relationship. The pioneer work of Bischof (1846), the founder of chemical geology, Bunsen (1851), and Senft (1857) led the way to the researches of Roth, Clarke, and Hillebrand, and culminated in Washington's awe-inspiring volume, *Chemical Analyses of Igneous Rocks* (1903), Cross, Iddings, Pirsson, and Washington's *Quantitative Classification of Igneous Rocks* (1903), and Clarke's *Data of Geochemistry* (4th ed., 1920)—three American works which are essential handbooks for geologists and chemists of all countries.

But while it is generally admitted that chemical composition is the most fundamental characteristic of rocks, it is ob-

vious that the most precise determination of the chemical constituents of all the rocks in existence would not in itself explain the origin of rocks or contribute more than unrelated facts to the history of the earth. In order to gain the truths of rock history it is necessary to know the processes which cause the results and the conditions under which these processes operate. On the basis of chemical composition, by theoretical and to a small extent by experimental methods, interesting attempts were made during the last quarter of the nineteenth century to determine the order in which minerals crystallize from a molten mass (magma) and the conditions responsible for the differentiation of magmas into chemical groups. As at other stages in the history of petrology, the problem was recognized but the known methods were inadequate.

The gateway to further research was opened by physical chemistry. With the development of this new science and the consequent improvement in experimental methods came the possibility of reproducing in the laboratory the work of underground forces and of recording the stages through which rocks and minerals pass from undifferentiated masses of molten or liquid material to their final form as quartz, granite, or marble.

In view of modern developments it is interesting to recall pioneer experiments. To disprove the teaching of the all-powerful German school of his day that basalt (lava) was precipitated from water, Sir James Hall in the year 1800 melted lavas from Etna and Vesuvius and allowed the mass to cool. Solid crystalline rock material resulted. Daubrée (1857) made quartz and feldspar from an aqua-igneous complex, proving that the conditions necessary to produce "granite-grained" igneous rock were moderate temperatures and presence of water vapor. Fouqué and Michel-Lévy (1878) produced augite-andesite with well-developed crystals by fusing selected ingredients in a dry state, holding the fused mass at a high temperature for forty-eight hours, and then allowing it to

cool. These brilliant researches of French geologists were carried still farther by Vogt and by other European scholars. But the world center for the experimental study of rock genesis is the Carnegie Geophysical Laboratory at Washington,[8] where under ideal conditions a corps of physicists, chemists, mineralogists, and petrologists are solving the deeper problems of rock genesis and rock relationship.

The Making of Mountains

Since the dawn of human history, even the uncritical observer must have noted that rock masses differ not only in color and composition but also in attitude; that some strata lie flat, others are tilted, still others are folded and buckled or broken. On the theory of a ready-made earth such facts occasioned no comment, but as the evidence accumulated that changes large and small have affected the earth's surface, speculations regarding the causes and processes of rock disturbance and of the origin of mountains were in order.

To observers of the seventeenth century earthquakes were an all-sufficient cause. Hooke (1688)[9] expressed the belief:

> Earthquakes have turned plains into mountains and mountains into plains, seas into land and land into seas, made rivers where there were none before, and swallowed up others that formerly were.

Woodward (1695)[10] cut the knot with the statement,

> the whole terrestrial globe has been taken to pieces at the flood and the strata settled down from this promiscuous mass.

Burnet[11] took the same view, and the state of knowledge of the times may be judged from the fact that his theory of the

[8] *Cf.* Sosman, R. B., in A Century of Science in America, 1918.

[9] Hooke, Robert, Posthumous Works, ed. R. Waller, London, 1705.

[10] Woodward, John, Essay towards a Natural History of the Earth, 1695.

[11] Burnet, Thomas, Telluris theoria sacra, London, 1681. Eng. trans., 1684.

earth (1690), thoroughly unsound in matter, method, and conclusions, was praised in a Latin ode by Addison and highly commended by Steele.

During the eighteenth century the view prevailed that all rocks were originally horizontal and that departures from this attitude were local and sufficiently accounted for by landslides, by cavities into which rocks fell, by volcanoes, and by original deposition in addition to the ever ready earthquake or flood which played the title rôle. As late as 1823 the easterly dip of the Connecticut River sandstone is ascribed by Hitchcock to "some Plutonian convulsion."[12]

Towards the close of the eighteenth century belief in the ability of streams and waves to corrade the surface, and to carry débris into the ocean, gained general acceptance. This belief, carried to its logical conclusion, meant that all dry land would ultimately disappear unless some forces were acting to re-elevate the continents. Earthquakes might break strata and volcanoes scatter the material about, but their effect is local and it was difficult to imagine how they might raise and depress the sea floor, build high mountains, or even produce the folds and contortions characteristic of many regions. Even the advocates of the Noachian flood were forced to depart from the literal description and call in comets and sudden shifting of the earth's axis to account for the seemingly disorganized earth with marine shells miles high on mountains. It was seen that some new mechanism must be devised, but the accepted teachings of the eighteenth and early nineteenth centuries allowed no place for an additional agent. Out of this *impasse* geology was led by James Hutton—successful physician, farmer, and manufacturing chemist. Discarding speculation and tradition and all concern for origins of things, this "pa-

[12] Hitchcock, Edward, Geology, etc., of the Connecticut Valley, Am. Jour. Sci., 6, 1823.

tient, enthusiastic, level-headed devotee of science" observed phenomena and processes, and developed a logical theory which lies at the base of modern dynamical geology. Hutton's *Theory of the Earth with Proofs and Illustrations* (1795) and its companion volume, Playfair's *Illustrations of the Huttonian Theory* (1802) are classics in geologic literature, which are scarcely out of place in a modern classroom. The scheme as outlined by Hutton is simple and convincing. Observation taught him that the features of the earth are not rigid and immutable but are continuously undergoing changes. Rocks decay, soil is swept away by streams, coasts are worn down, and all loose material is carried to the sea. In time the solid lands must disappear. The débris is deposited on the ocean floor, forming layers in which remains of organisms are embedded. The material for making future lands is thus prepared. But to be recovered from the sea and built into continents these sediments must be elevated. In searching for an agent capable of causing uplift, Hutton dismissed as phantoms the "convulsions of nature," "emanations," and "universal debacles" of his contemporaries and predecessors. Going once more to the field, he observed that many rocks are not stratified and many are bare of fossils, and that these rocks show unmistakable evidence that they were once in a molten state; in fact, that some of the igneous materials have come up from below, penetrated the surrounding rocks, and altered their appearance and composition. Deep within the earth, therefore, heat must prevail and the sudden expansion of rocks induced by heat not only produced volcanoes but lifted the overlying rock masses. Rugged mountains, broken and tilted strata, and folds are witnesses to these gigantic upheavals.

Hutton's teachings were a half-century ahead of his time and made slow headway. Though supported by the nebular hypothesis of a cooling globe, by the testimony of miners that

heat increases with depth, and by the evidence of volcanoes as presented by Desmarest (1725-1815) and by Scrope (1823), the hypothesis of universal and subterranean heat was ignored or combated by the strongly entrenched Wernerian school, which clung to the view that all rocks are formed from water, that mountains are gigantic crystalline aggregates made where they stand, and that the earth is cold to the center. Professor Jameson, a colleague of Playfair at Edinburgh University, writing in 1808,[13] calls the researches of Hutton, Playfair, and Hall "monstrosities" and remarks: "It is therefore a fact that all inclined strata with few exceptions have been formed so originally and do not owe their inclination to subsequent change." Fortunately for science Hutton was followed by Lyell (1797-1875). Taking for his text the saying of Hutton, "Amid all the revolutions of the globe, the economy of nature has been uniform," Lyell expounded and systematized the theories of his master, gathered new facts, pointed out errors, and through his *Principles of Geology* guided the thought of students during the second quarter of the nineteenth century. Lyell's chief contribution was the development of the thesis that the forces operating on and within the earth during past time are the same as those of today; that knowledge of past events is to be gained by studying present processes. The building of mountains and continents, the folding and breaking of strata, the making of igneous and sedimentary rocks, and the entombment of fossils are proceeding as rapidly and in the same manner as in other ages. There have been no "gigantic cataclysms" or "devastating floods"; all processes have been orderly and uniform in degree and in kind. The emergence and submergence of coasts, the changes of level associated with earthquakes, are the rule not exceptions, and do not involve unusual forces.

[13] Jameson, Robert, Elements of Geognosy, Edinburgh, 1808.

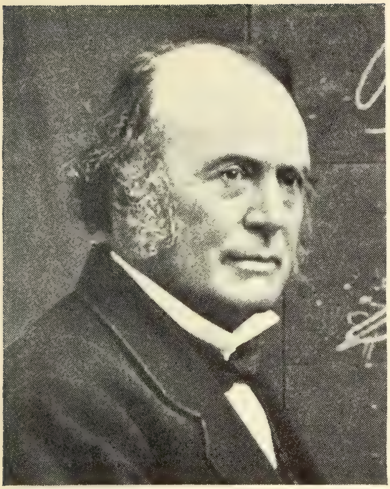
> The land has never in a single instance gone down suddenly for several hundred feet at once. . . . Great but slow oscillations have brought dry land several thousand feet below sea and raised it thousands of feet above. Places now motionless have been in motion and places of present active movements were formerly stationary.

Although this doctrine of "uniformitarianism" was carried by Lyell somewhat beyond the modern viewpoint, the road to progress was cleared of fantastic speculations.

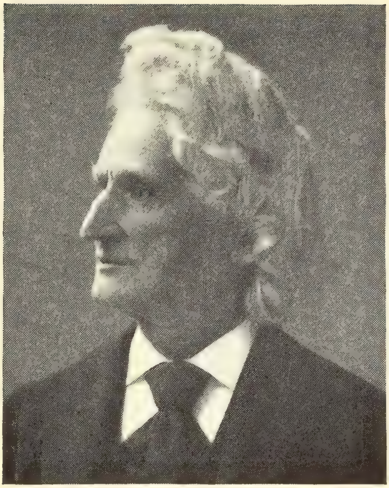
Hutton and Lyell considered heat combined with pressure sufficient cause for vertical uplifts of parts of the earth's surface. The analyses of these processes have absorbed the attention of structural geologists down to the present day. In 1833 the brilliant French scholar, Elie de Beaumont (1798-1874), expressed the view that the earth is a fused mass covered by an envelope of cooled rock "thinner in proportion than the shell of an egg." In adjusting itself to the cooling interior this crust became wrinkled. From time to time portions of the crust collapsed along definite lines of fracture. At such times the rocks are subjected to great lateral pressure; the unyielding ones are crushed, the pliant ones bent and forced to pack themselves into smaller space. The readjustment of the shell to the shrinking interior causes portions of the crust to be squeezed upwards as wrinkles or folds which we call mountain ranges. By reference to the surrounding rocks, the date of the mountain's birth is obtained.

These views, although in part erroneous and discounted even during the lifetime of their author, marked an important advance, for through them came the idea of mountain folding by lateral compression. As treated by James D. Dana,[14] this conception grew into a consistent theory of mountain origin and structure which has received universal acceptance. In brief, this theory is as follows: Materials for the future mountain

[14] Dana, J. D., Manual of Geology, Philadelphia, 1863, 3d ed., 1880.



Louis Agassiz.



James Dwight Dana.

Sir Roderick Impey Murchison.

William Buckland.

system are eroded from a land mass and deposited in a progressively sinking trough to a thickness of thousands of feet. After long ages the sediments in the trough are compressed laterally against the relatively solid old land; the shortening, amounting to many miles (Appalachians, 40 miles; Alps, 74), is made possible by folding or by forcing parts to override other parts. During and after the periods of folding and faulting the newly born mountain range is eroded into features which are recognized as ridges, peaks, and valleys. These processes, which in detail are enormously complicated, involve regional upwarps and downwarps which are recorded over wide areas. Largely through a study of mountain ranges with their faults and folds and enormous thicknesses of disturbed sedimentary and igneous rocks has come the modern view of the fundamental structural relations: that the earth is not a liquid or molten mass covered with a crust, but a globe as rigid as a ball of steel or glass of equal dimensions yet "plastic" or "pliable" enough to yield under the weight of even a moderate load.

Interpretation of Natural Scenery

A discussion of the principles and processes involved in sculpturing the earth surface was futile on the hypothesis of a ready-made earth whose features were unchangeable except when modified by catastrophic action. The belief in the Deluge as the one great event in geological history effectually checked investigation of the work of rivers, glaciers, wind, and the atmosphere in producing the variety of forms that constitute natural scenery. It is therefore not surprising that physiography, whose essence lies in the belief that present land forms represent merely a stage in the orderly development of the earth's surface features, should have attained the dignity of a science within the past quarter-century; nor that the specula-

tions of Aristotle, Herodotus, Strabo, and Ovid, and the illustrious Arab, Avicenna (980-1037), unchecked by appeal to facts but also unopposed by priesthood or popular prejudice, are nearer to the truth than the intolerant controversial writings of the intellectual leaders of the late Middle Ages whose touchstone was orthodoxy. Stensen (1638-1687) mildly suggested that surface sculpturing, particularly on a small scale, is largely the work of running water, and Guettard (1715-1786) grasped the fundamental principles of denudation; but nearly eighteen centuries had elapsed before Desmarest, the father of physiography, presented proofs that valleys are made by rivers and that a landscape passes through clearly defined stages of development.

Desmarest's teachings were strengthened and expanded by de Saussure (1740-1799),[15] the originator of the term "geology," who saw in the intimate relation of Alpine streams and valleys the evidence of erosion by running water (1786).

These works from the acknowledged leaders of geological thought of the period aroused singularly little interest on the continent, and Lamarck's volume on denudation (*Hydrogéologie*), which appeared in 1802, although an important contribution, sank out of sight. But the seed of the French school found fertile ground in Edinburgh, the hub of the geological world at the close of the eighteenth century. Hutton's *Theory of the Earth, with Proofs and Illustrations,* in which the guidance of de Saussure and Desmarest is gratefully acknowledged, appeared in 1795. The original publication aroused only local interest, but when placed in attractive form by Playfair,[16] the problem of the origin and development of land forms assumed a permanent position in geological thought. Steps in the analysis and solutions of these problems

[15] Saussure, H. H. de, Voyage dans les Alpes, 1779-1796.
[16] Playfair, John, Illustrations of the Huttonian Theory, 1802.

may be illustrated by tracing the growth of ideas regarding valleys and features produced by glaciation.

In the interpretation of valleys little progress was made during the first fifty years of the nineteenth century. Physiographic literature shows that the clear reasoning of Desmarest, de Saussure, Hutton, and Playfair, firmly buttressed by concrete examples, was insufficient to overcome the belief that valleys are ready made or result from cataclysms and that the corrugations and irregularities of mountain surface are remnants of the primeval earth. The principles laid down by these clear-sighted leaders were too far in advance of their time to secure general acceptance. In a paper with the significant title, "Bursting of Lakes through Mountains," Wilson (1821) asks: "Is it not the best theory of the earth, that the Creator, in the beginning, at least at the general deluge, formed it with all its present grand characteristic features?"[17]

In 1823 Buckland[18] wrote:

> . . . The general belief is that existing streams, avalanches and lakes, bursting their barriers, are sufficient to account for all their phenomena. It is now very clear to almost every man, who impartially examines the facts in regard to existing valleys, that the causes now in action . . . are altogether inadequate to their production; nay, that such a supposition would involve a physical impossibility. . . . We do not believe that one-thousandth part of our present valleys were excavated by the power of existing streams.

Similar views were expressed in scientific journals of Europe and of America by the leaders of geologic thought, including Hitchcock (1824),[19] Phillips (1829),[20] Lyell (1833), Con-

[17] Wilson, J. W., Bursting of Lakes through Mountains, Am. Jour. Sci., III, 253, 1821.

[18] Buckland, William, Reliquiæ diluvianæ, review in Am. Jour. Sci., 8, 1824.

[19] Hitchcock, Edward, Geology, Mineralogy, and Scenery of Regions contiguous to the Connecticut River, with a geological map and drawings of organic remains (etc.), Am. Jour. Sci., 7, 1824.

[20] Phillips, John, Geology of Yorkshire, Am. Jour. Sci., 21, 1832.

rad (1839),[21] Darwin (1844),[22] Warren (1859),[23] and Lesley (1862).[24]

By the middle of the nineteenth century opinion regarding valleys had become standardized somewhat as follows: the position of many valleys is determined by original surface inequalities or by later fractures in the earth's crust; most of them are intimately associated with earthquakes, bursting of lakes, or the sudden upheavals or depressions of the land; valleys of erosion are chiefly the work of the sea, but rivers may perform similar work on a small scale.[25] The extent of the wandering from the guidance of de Saussure and Playfair after the lapse of fifty years is shown by students of Switzerland. Alpine valleys to Murchison (1851) were bays of an ancient sea; Schlagintweit (1852) found regional and local complicated crustal movements a satisfactory cause; and Forbes (1863) saw only glaciers.

The truths expounded by Desmarest and Hutton were reestablished by James D. Dana,[26] who in 1850 amply demonstrated that valleys on the Pacific islands owe neither their origin, position, nor form to the sea or to structural factors, but are the work of existing streams which have eaten their way headwards. Even the valleys of Australia cited by Darwin as type examples of ocean work are shown to be products of normal stream action. Dana went further and gave a permanent place to the Huttonian idea that many bays, inlets, and

[21] Conrad, T. A., Notes on American Geology, Am. Jour. Sci., 35, 1839.

[22] Darwin, C. R., Geological Observations, etc., during the Voyage of the "Beagle," London, 1844.

[23] Warren, G. K., Explorations in Nebraska and Dakota, review in Am. Jour. Sci., 27, 1859.

[24] Lesley, J. P., Observations on the Appalachian Region of Southern Virginia, Am. Jour. Sci., 34, 1862.

[25] *Cf.* Gregory, H. E., Steps of Progress in the Interpretation of Land Forms, in A Century of Science in America, pp. 124-152, 1918.

[26] Dana, J. D., On Denudation in the Pacific, Am. Jour. Sci., 9, 1850; On the Degradation of the Rocks of New South Wales and Formation of Valleys, *ibidem.*

fiords are but the drowned mouths of river-made valleys. The theory that valleys are excavated by streams which occupy them received strong support from study of the Rocky Mountain gorges (1862) and gained all but universal acceptance after Newberry[27] called attention to the lesson to be learned from the canyons of Arizona:

> Like the great cañons of the Colorado, the broad valleys bounded by high and perpendicular walls *belong to a vast system of erosion, and are wholly due to the action of water.* . . . The first and most plausible explanation of the striking surface features of this region will be to refer them to that embodiment of resistless power—the sword that cuts so many geological knots—volcanic force. The Great Cañon of the Colorado would be considered a vast fissure or rent in the earth's crust, and the abrupt termination of the steps of the table-lands as marking lines of displacement. This theory though so plausible, and so entirely adequate to explain all the striking phenomena, lacks a single requisite to acceptance, and that is *truth.*

With these stupendous examples in mind, the dictum of Hutton seemed reasonable: "There is no spot on which rivers may not formerly have run."

Contributions to physiography between 1850 and 1870 reveal a tendency to accept greater degrees of erosion by rivers, but the necessary end-product of subaerial erosion—a plain—is first clearly defined by Powell (1875),[28] who introduced the term "base level," which may be called the germ word out of which has grown the "cycle of erosion," the master key of modern physiographers.

Analysis of Powell's view has given definiteness to the distinction between "base level," an imaginary plane, and a "nearly featureless plain," an actual land surface, the final product of subaerial erosion. Following their discovery in the

[27] Newberry, J. S., Colorado River of the West, review in Am. Jour. Sci., 33, 1862.

[28] Powell, J. W., Exploration of the Colorado River of the West, 1875.

Colorado Plateau Province, denudation surfaces were recognized in Pennsylvania by McGee,[29] and in Connecticut by Davis (1889)[30] who introduced the term "peneplain," "a nearly featureless plain," for the upland of southern New England developed during Cretaceous time.

Long before the days of Powell "plains of denudation" had been clearly recognized by English geologists, who considered them products of marine work. The contribution of American students is not that peneplains exist but that many of them are the result of normal subaerial erosion. More precise field methods during the past decade have revealed the fact that no one agent is responsible for the land forms classed as peneplains; that not only rivers and ocean, but ice, wind, structure, and topographic position must be taken into account.

The recognition of rivers as valley-makers and of the final result of their work necessarily preceded an analysis of the process of subaerial erosion. The first and last terms were known, the intermediate terms and the sequence remained to be established. Significant contributions to this problem were made by Jukes' (1862) discussion of "lateral" and "longitudinal" valleys, Powell's description of antecedent and consequent drainage (1875), and Gilbert's analysis of land sculpture in the Henry Mountain (1880). But the master papers are by Davis,[31] who introduces an analysis of land forms based on structure and age by the statement:

Being fully persuaded of the gradual and systematic evolution of topographical forms it is now desired . . . to seek the causes of the location of streams in their present courses; to go back if possible to the

[29] McGee, W. J., Three Formations of the Middle Atlantic Slope, Am. Jour. Sci., 35, 1888.

[30] Davis, W. M., Topographic Development of the Triassic Formation of the Connecticut Valley, Am. Jour. Sci., 37, 1889.

[31] Davis, W. M., The Rivers and Valleys of Pennsylvania, Nat. Geog. Mag., 1, 1889; The Rivers of Northern New Jersey with Notes on the Classification of Rivers in General, *ibid.*, 2, 1890.

early date when central Pennsylvania was first raised from the sea, and trace the development of the several river systems then implanted upon it from their ancient beginning to the present time.

That such a task could have been undertaken only three decades ago and today be considered a part of everyday field work shows how completely the lost ground has been regained and how rapid has been the advance in the knowledge of land sculpture since the canyons of the Colorado Plateau were interpreted.

One of the most interesting chapters in geological history is the origin and development of the theory of continental glaciation, which grew out of the attempt to explain the presence of "erratic" boulders strewn over the surface in "obviously unnatural" positions. As stated by Silliman (1821):[32]

> The almost universal existence of rolled pebbles, and boulders of rock, not only on the margin of the oceans, seas, lakes, and rivers; but their existence, often in enormous quantities, in situations quite removed from large waters; inland,—in high banks, imbedded in strata, or scattered, occasionally, in profusion, on the face of almost every region, and sometimes on the tops and declivities of mountains, as well as in the valleys between them; their entire difference, in many cases, from the rocks in the country where they lie—rounded masses and pebbles of primitive rocks being deposited in secondary and alluvial regions, and vice versa; these and a multitude of similar facts have ever struck us as being among the most interesting of geological occurrences, and as being very inadequately accounted for by existing theories.

To this list of features now recognized as characteristic of glacial drift are to be added jumbled masses of "diluvium," ridges of gravel, "kettles" in sand plains, polished and striated rock, and thick beds of "unhardened pudding stone" (till). Even Lyell, the great exponent of uniformitarianism, appears

[32] Silliman, Benjamin, Notice of Hayden's Geological Essays, Am. Jour. Sci., 3, 1821.

to have lost faith in his theories when confronted with facts for which known causes seemed inadequate.

The interest aroused by the phenomena now attributed to ancient glaciers is attested by scores of titles in scientific and literary periodicals of the first four decades of the nineteenth century. With little knowledge of existing glaciers, of areal distribution, structure and composition of drift, all known forces were called in: weathering, catastrophic floods, ocean currents, waves, icebergs, glaciers, wind, and deposition from a primordial atmosphere. Even human agencies were not discarded. But the controversy ranged chiefly about floods, icebergs, glaciers, and earth-shaking catastrophes.

The catastrophes favored by most geologists were the Deluge, and floods of water violently released from the interior of the earth or caused by sudden upheaval of mountains. "We believe," says Silliman (1824) "that all geologists agree in imputing . . . the diluvium to the agency of a deluge at one period or another"[33]—a conclusion which rested in no small way upon Hayden's[34] well-known treatise on "diluvium" (surficial deposits, glacial drift). The objection to the theory of "debacles" and resistless world-wide currents is not only its grotesque assumptions and processes but also its complete disregard of observable phenomena. Its strength lay chiefly in its supposed confirmation of the biblical record and it is perhaps natural that the way to a saner view should have been pointed out by intelligent laymen rather than by leaders of thought bound by authority and tradition. Unbiased observation is an essential condition of progress.

In 1823[35] Granger speaks of the glacial striæ on the shore of Lake Erie as

[33] Silliman, Benjamin, Review of Hayden's Geological Essays, Am. Jour. Sci., 6, 1824.

[34] Hayden, H. H., Geological Essays, Am. Jour. Sci., 3, 1821.

[35] Granger, Ebenezer, Notice of a Curious Fluted Rock at Sandusky Bay, Ohio, Am. Jour. Sci., 6, 1823.

having been formed by the powerful and continued attrition of some hard body. . . . To me, it does not seem possible that water under any circumstances, could have effected it. The flutings in width, depth and direction, are as regular as if they had been cut out by a grooving plane. This, running water could not effect, nor could its operation have produced that glassy smoothness, which, in many parts, it still retains.

The first unequivocal statement that ice is an essential factor in the formation and transportation of drift comes from another layman, Peter Dobson (1826),[36] who concludes a series of accurate detailed observations on the polished and striated boulders embedded in the Connecticut till with the remark:

I think we cannot account for these appearances, unless we call in the aid of ice along with water, and that they have been worn by being suspended and carried in ice, over rocks and earth, under water.

The glacial theory makes its way into geological literature with the development by Agassiz (1837) of the views of Venetz (1833) and Charpentier (1834) that the glaciers of the Alps once had greater extent. The bold assumption was made that the surface of Europe as far south as the shores of the Mediterranean and Caspian seas was covered by ice during a period immediately preceding the present. The kernel of the present glacial theory is readily recognizable in these early works, but it is wrapped in a strange husk: the Alps were assumed to have been raised by a great convulsion under the ice and the erratics to have slid to their places over the newly made declivities. The publication of the famous *Études sur les Glaciers* (1840), remarkable alike for its clarity, its sound inductions, and wealth of illustrations, brought the ideas of Agassiz into prominence and inaugurated a thirty years' war with the proponents of floods and of icebergs. The outstanding objections to the theory were the requirement of a frigid climate and the demand for glaciers of continental dimensions;

[36] Dobson, Peter, Remarks on Bowlders, Am. Jour. Sci., 10, 1826.

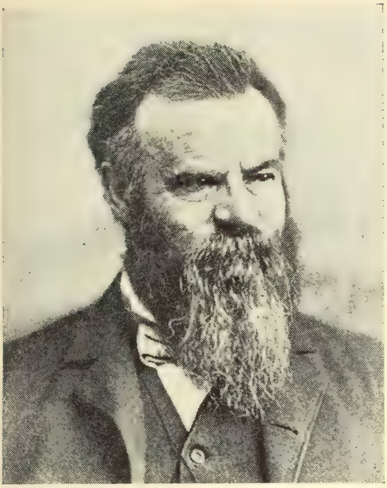
very strong objections for the time when fossil evidence was not available, the great polar ice sheets were unexplored, and the distinction between till and water-laid drift had not been established.

So fully does the glacial hypothesis account for observed phenomena that it received the sympathetic attention of leading geologists, especially in America. As the evidence accumulated, opposition disappeared, and by 1875 the belief in the former wide extent of land ice was firmly established.[37] The next step forward was the determination of the extent of glacial drift—a series of field studies that have produced the modern maps of glaciated areas and led to the interesting conclusion that the "ice age" was not the record of the advance and retreat of one great continental glacier, but that it is divided into epochs; that several retreats are required to account for the phenomena of buried soils and overlapping ice-laid deposits. In 1883 Chamberlin[38] presented his views, under the bold title "Preliminary Paper on the Terminal Moraine of the Second Glacial Epoch," which initiated the discussion that led to the recognition of glacial deposits of different ages and the features of interglacial periods. Field studies during the last quarter-century have demonstrated five glacial stages in America and four in Europe.

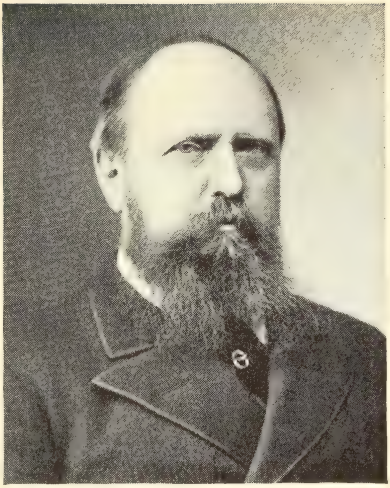
Within the present generation sculpture by glaciers has received much attention and has involved a reconsideration of the ability of ice to erode, which in turn involves a crystallization of views of the mechanics of moving ice. The inadequacy of structural features or of river corrasion to account for flat-floored, steep-walled gorges, hanging valleys, and many lake basins, has led to the present fairly general belief in the long

[37] Gregory, H. E., Steps of Progress in the Interpretation of Land Forms, *op. cit.*

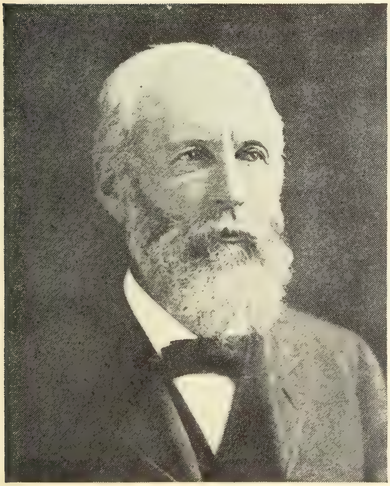
[38] Chamberlin, T. C., Preliminary Paper on the Terminal Moraine of the Second Glacial Period, U. S. Geol. Survey, Third Ann. Rept., 1883.



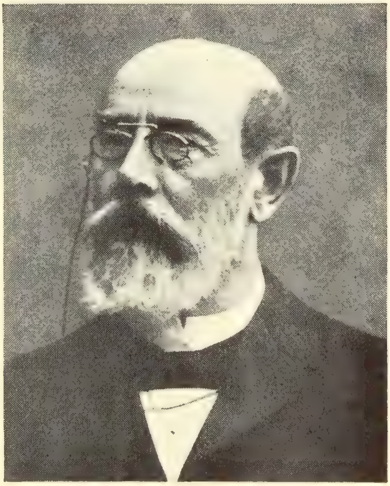
John Wesley Powell.



Othniel Charles Marsh.



Grove Karl Gilbert.



Harry Rosenbusch.

neglected views of Ramsay that glaciers are powerful agents of rock sculpture. The details of the process, particularly of the sculpturing of cirques, are not yet fully understood.

Meaning of Fossils

From the time when fossils received general recognition as the remains of extinct organisms, they have been examined from two viewpoints. One group of students (stratigraphers) are interested in fossils as objects which characterize geological epochs and by means of which true succession and relative ages may be determined. The other group (paleozoologists and paleobotanists) find the supreme value of fossils in their bearings on the problems of origin, development, and evolution of living forms. It is this biological aspect which has aroused an almost universal interest in fossils, brought the teachings of geology into zoological laboratories and medical schools, and furnished material for controversy to theologians and philosophers. The founders of paleontology, Blumenbach (1803-1816), Schlotheim (1804), Sternberg (1804), Cuvier (1808), Lamarck (1815-1822), and Brongniart (1822), attained success by applying the methods of comparative anatomy and botany, and the subject found an assured position through the work of Buckland (1836), Mantell (1844), Pictet (1844-1846), Geinitz (1846), Quenstedt (1852), and Richard Owen (1860)—all primarily biologists. Vertebrate paleontology especially has been treated as a branch of comparative anatomy concerned primarily with fossil bones and teeth, but its contributions have brought the civilized world to a belief in the theory of organic evolution.

Fossils were correctly considered by the Greeks and Romans as remains of plants and animals, but their presence in the rocks was ascribed to gigantic inundations which had brought marine animals far inland. Avicenna (980-1037), the great Arabian scholar, thought fossils were the unfinished work of

vis plastica, a creative force that changed inorganic substances to organic; the living form had been produced but no life given it. To Georg Bauer [Agricola] (1494-1555), and to Mattioli (1548), fossils were "solidified accumulations from water" like limestone, or converted into stones by a certain *succus lapidescens* believed to reside in water; to the anatomist Falloppius fossil teeth were concretions and fossil shells the result of "fermentations" and "exhalations from the soil"; to Olivi of Cremona they were mere sports or freaks; Lister (1638-1711) taught that each rock stratum produces its own fossils; Mercati, museum assistant to Pope Sixtus V, thought them seeds of the stars; and the English antiquary Lhuyd (Luidius) sought their origin in seed-bearing vapors originating in the sea. These typical seventeenth century ideas of the nature of fossils are to be contrasted with those of Leonardo da Vinci (1452-1519) and Fracastoro (1483-1553), who insisted that fossils are organisms which once lived where now found, and which owe their preservation to burial in mud.

The conclusions of these Italian scholars who ridiculed the notion that fossils descended from stars or were formed in the earth by some mysterious creative force were disregarded or treated as "vaporings of disordered minds"; Bernard Palissy (1499-1589), who near the close of the sixteenth century gave a correct explanation of petrified wood, fossil fish, and molluscs, was vigorously denounced as a heretic. Even the teachings of the remarkable scholar, Niels Stensen (Nicolaus Steno, 1638-1686), whose little pamphlet *De solido intra solidum naturaliter contento* (1669) is the high-water mark of seventeenth century geology, made little impression and was soon forgotten, and at the beginning of the eighteenth century fossils were generally considered mineral curiosities—"formed stones," "figured stones"—and chance imitations of living forms.

Fortunately the disputes regarding the nature of fossils en-

couraged the search for fossils and led to a number of valuable works in which fossils were faithfully described and represented by drawings. Publications descriptive of fossils of particular regions, monographs on selected groups, and general treatises on classification and nomenclature appeared in France, England, Germany, Switzerland, and Italy during the early part of the eighteenth century. Through the labors of Scheuchzer[39] and many supporters, Johann Baier,[40] and especially John Woodward,[41] and Knorr and Walch,[42] whose handsome four-volume treatise is the paleontological masterpiece of that period, trilobites, brachiopods, molluscs, crinoids, sponges, crabs, fishes, and vertebrate bones were made known to the scientific world. The accumulated evidence was conclusive and at the middle of the eighteenth century no scholar of repute looked on fossils as the result of inorganic forces.

With the recognition of fossils as the remains of living beings, the three-century discussion of the origin of fossils assumed new form. Are these objects the *relictæ* of animals and plants now living or do they represent peculiar races of animals and plants which formerly inhabited the earth? Have they originated where found or have they been transported to their present resting places, and if transported, by what agency? With the fauna of half the earth's surface and the life of the ocean unknown it was but natural to assume that fossil snails and oysters and leaves belonged to species of animals and plants which still flourished in some unexplored part of the world. It was commonly believed that the only animals in existence were those made during the days of creation and that none had disappeared from the world. Thus the bones

[39] Scheuchzer, J. J., Specimen lithographie helveticæ curiosæ, 1702.

[40] Baier, Johann, Oryctographica norica, 1712.

[41] Woodward, John, *op. cit.*

[42] Knorr, G. W., and Walch, J. E. F., Die Sammlung von Merkwürdigkeiten der Natur und Alterthümer des Erdbodens.

of the ground sloth (*Megalonyx jeffersoni*) described by Thomas Jefferson were believed by him to be the remains of some sort of a lion still living in the Alleghany Mountains. But the hope of finding living specimens to match the skeletons embedded in the rock resulted in disappointment and in the search for other explanations the theory of great catastrophes which overwhelmed the inhabitants of all or parts of the earth gained the support of the leading minds towards the close of the eighteenth century. Great inundations of the sea, terrific earthquakes, and gigantic volcanic eruptions all had their supporters, but the belief in Noah's flood enlisted the most faithful adherents. The biblical flood not only swept the earth of living forms, but scattered their remains far and wide and left them buried in jumbled heaps in the sands and muds deposited by the onrushing currents. Warmly approved by the church, the "diluvialists" occupied a strong position in the scientific world well into the nineteenth century. Even the great Cuvier (1821) lent support to the believers in the flood and Buckland's treatise on the *Organic Remains Contained in Caves, Fissures and Diluvial Gravel, and on Other Phenomena Attesting the Action of a Universal Deluge,* bears the date 1823.

With a wider recognition of the fact that fossils are not restricted to sands and gravels and muds which might have been deposited within the past few thousands of years, but are found embedded in firm rock on plains and seashore and mountain tops and are revealed by mine shafts, wells, tunnels, and excavations for buildings, the diluvial hypothesis assumed yet another form. Noah's flood was retained, but was given the position of the last of a series of great catastrophes which overwhelmed the world.

Under the lead of the French paleontologists, cordially supported by their English and American colleagues, the "catastrophists" held sway during the first six decades of the nine-

teenth century. They clearly recognized that fossils in a given formation differed in kind from those in the overlying and underlying strata, but explained these facts on the theory that the period represented by each of these formations witnessed the complete disappearance of animal and plant life of the world. The fossils of the next higher strata were the remains of newly created beings. Each species was a separate creation. The simplicity of forms of the earlier creations compared with the complexity of form and structure of the fossils of later creations appears to have been ascribed to the progressive skill of the Creator rather than to the progressive development of species.

Cuvier, the leader of the catastrophic school, is the outstanding figure among the paleontologists of the first half of the nineteenth century. As a biologist he established comparative anatomy as a distinct branch of science and formulated the principles and methods still in vogue for the study of fossil vertebrates. Through his influence systematic research replaced disorganized observation. His conception of the correlation of parts, that structure and function are interdependent, is the guiding principle in modern paleontology, and makes it possible to reconstruct an extinct animal from fragmentary remains found in the rocks or even from a single bone or tooth. His work shows a progression from description of individual bones to reconstruction of whole skeletons, and on to the grouping of extinct forms into species, genera, and orders. The wealth of fossil material embedded in the gypsum deposits of the Paris Basin "enabled him to prepare the first reconstructions of fossil vertebrates ever attempted and to bring before the eyes of his contemporaries a world peopled with forms which were utterly extinct."[43] To bring to the laboratory a miscellaneous assemblage of fossil bones and by the strict

[43] Lull, R. S., On the Development of Vertebrate Paleontology, in A Century of Science in America, E. S. Dana, Editor, 1918.

application of scientific method supply the missing parts until there appears an animal never before seen by human eye, may be considered one of the great achievements of the human mind. Little wonder that Cuvier's demonstrations revolutionized the thought of his day and made a deep and lasting impression. Paleontological views before the days of Darwin were essentially the views of Cuvier and his devoted disciples. Most of the epoch-making contributions of the Cuvierian school have remained undisputed, but the contention that species are immutable is strangely out of harmony with modern views.

When the Cuvierians left the solid ground of their field of comparative anatomy they parted company with contemporary thinkers in other branches of geology and entered the bog already thickly populated with philosophers, theologians, and mystics of ancient and medieval times. Unconsciously and with different terminology, they gave their approval to Indian, Egyptian, and early Church beliefs in earth catastrophes followed by re-creations—periods of disaster interspersed with millenia. There was no recognition of the orderly development of the earth and its inhabitants resulting from the operation of natural laws.

The publication of Darwin's *Origin of Species,* 1859, marks the beginning of the evolutionary period in the study of fossils. The fixity of species was replaced by the evolution of species; recurrent catastrophes which necessitated new creations retired in favor of orderly development; and supernatural agencies were discarded. This revolutionary change in thought was foreshadowed by the teachings of a few bold spirits and the transition from catastrophism to evolution made easier by evidence accumulated during previous decades.

By 1865, two thousand fossils from strata later than the Carboniferous were known in America; and more than twenty thousand in Europe. A study of this material led to the recogni-

tion of the facts that the individuals which compose a species are "endlessly diverse" (Dana); "that fossils from two consecutive formations are far more closely related than are the fossils of two remote formations" (Asa Gray); "that when species are arranged in a series and placed near to each other with due regard to their natural affinities they each differ in so minute a degree from those next adjoining that they almost melt into each other" (Lyell). And during the catastrophic period men were not lacking who accepted the evidence of transition in the organic world and followed it to its logical conclusion. Aristotle's views are singularly like those of modern time and Erasmus Darwin (1731-1802), grandfather of Charles Darwin, consistently taught that variations in species arise within organisms in response to environmental influences. Comte de Buffon (1707-1788) grasped the idea that life descends continuously from other life and is modified by geographical isolation, but only the industrious and serious-minded can separate the wheat from the chaff in the forty-four volumes of his entertaining *Histoire Naturelle* (1749-1804).

Among evolutionists of pre-Darwin days, Chevalier de Lamarck (1744-1829) stands first. For fifty years he was a firm believer in catastrophes and re-creations, but in later life, in the face of strong opposition, he gave the full weight of his knowledge and experience to the support of the theory of descent and inheritance of acquired characters. His teachings are so unmistakably clear and so sharply contrasted with the contentions of the catastrophists that Lamarck is justly regarded as the founder of the evolutionary school. Lamarck's ideas were kept alive by a group of earnest but unconvincing followers including Geoffroy Saint-Hilaire and the poet Goethe, but such men were no match for the gifted scientists of the catastrophic school, supported as they were by the Church and by public opinion. Even the *Vestiges of the Natural History of Creation* by Robert Chambers (1802-1871),

the most discussed book of the time, failed to uproot traditional beliefs, and by 1850 the evolutionary theory was pronounced "dead" by the leading writers of the time.

The resurrection came with the publication of Darwin's *Origin of Species,* doubtless the most influential book of the nineteenth century No wonder that Darwin's views were received with dismay and aroused strenuous and bitter opposition, for their acceptance gave the death blow to creationists, placed man among the animals, and otherwise undermined the supposedly plain teachings of Scripture. The theory early received the support of Hooker, Huxley, and Herbert Spencer in England, and Asa Gray in America. Among its American opponents were James D. Dana, who later modified his opinion, and Louis Agassiz, who held his disapproval through life. That part of Darwin's theory which related to the progressive development of *living* plants and animals aroused little opposition, for improvements produced by the breeding of domesticated animals were well understood; but the testimony of the rocks that the lineal ancestors of existing animals are constituents of strata laid down millions of years ago was quite another matter.

The scientific opponents of evolution relied mainly on the fact, uncontested by geologists, that the successive strata did not disclose an unbroken series of modified forms—there were many "missing links" in the supposed chain of development. In this connection the discoveries of American vertebrate paleontologists make an interesting chapter. Beginning with 1870, Leidy, Cope, Marsh, followed by a group of workers of the present generation, unearthed the profusion of vertebrate remains from Tertiary, Cretaceous, and Jurassic beds which have made famous the collections in the American Museum of Natural History and the Peabody Museum at Yale. Professor Marsh alone found the remains of about 200 birds with teeth, 160 mammals, and hundreds of flying, swimming,

and walking reptiles varying in size from guinea pigs to monsters eighty feet long. These collections bridged the gap between reptiles and birds and indicated the common ancestors for animals now recognized as distinct species.

Back through successive geological epochs the modern horse was traced through transitional forms to a four-toed ancestor, the size of a fox, which flourished during the Eocene. Such evidence could not be disregarded. In reviewing the work of Marsh, Huxley, who previously had pointed out the insufficiency of the paleontological evidence, declared that "the evolution of existing forms of animal life from their predecessors is no longer an hypothesis but an historical fact" (1876).

Like other animals of the modern world, man's ancestry has been traced far back. The discovery of human bones and implements intermingled with the remains of animals long extinct proved a human habitation in France (Abbeville); Germany (Neanderthal: Fuhlrott, 1857); and England (Piltdown: Woodward, 1913) during Pleistocene time; and in Java (Du Bois, 1891) at perhaps an even earlier date.

The Geologic Time-Scale

Since the beginnings of field observations it has been known that many rocks are arranged in layers and that in many places strata of different colors and texture and composition are piled one upon another in a regular series. But nearly eighteen centuries elapsed before it was realized that the stratified rocks contain within themselves the evidences of their origin and reveal a record of alternating lands and seas, of volcanic outpourings and desert winds, of changing climates and surface forms. A yet longer time was required to grasp the stupendous truth that the history of life on the earth is to be deciphered from the organic remains embedded in the hardened sediments.

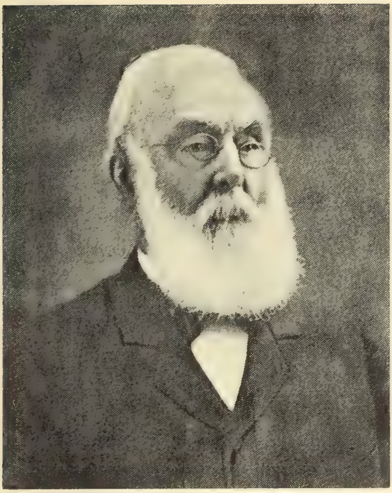
The true meaning of chronological sequence, the recognition of the fact that the débris of lower strata has been utilized in building the strata next above, was first made clear by Arduino (1713-1795), who separated the rocks of northern Italy into Primitive, Secondary, Tertiary, and Volcanic (1759). The field methods and manner of presentation developed by Arduino are not unlike those employed today and entitle this pioneer worker to a prominent place among stratigraphers.

An advance is shown in the work of Füchsel (1722-1773),[44] who analyzed the sedimentary masses of Thuringia. By his painstaking field mapping, his insistence that groups of strata have definite chronologic value, and especially by his clear distinction of stratum (Schicht) and formation (*Series montana*), were laid the foundations of stratigraphic geology in Germany.

The high priest of stratigraphy for the eighteenth century was Abraham Gottlob Werner (1749-1817), professor in the School of Mines of Freiberg—the first geologist to obtain world-wide prominence. Werner's contributions to literature are of small importance; his strength lay in his familiarity with the geological researches of his time and even more in his remarkable ability in teaching which made of Freiberg the Mecca for European students. Based on the conception of universal formations as developed by Füchsel, and on the systematic arrangement of minerals as outlined by the Swedish mineralogist, Tobern Bergman,[45] Werner erected the study of rock formations into an independent branch of geology. The essence of his teaching lies in the view that all rock formations are world-wide and that all are chemical precipitates; that the

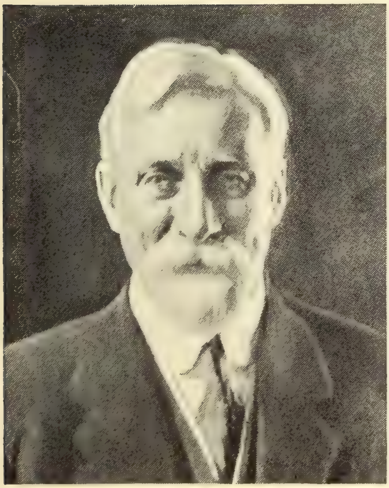
[44] Füchsel, G. C., Historia terræ et maris ex historia Thuringiæ permontium descriptionem erecta, Acta Acad. elect. Moguntinæ, 1762; Entwurf zur ältesten Erd und Menschen Geschichte, 1773.

[45] Bergman, Tobern, Physical Description of the Globe, 1766.

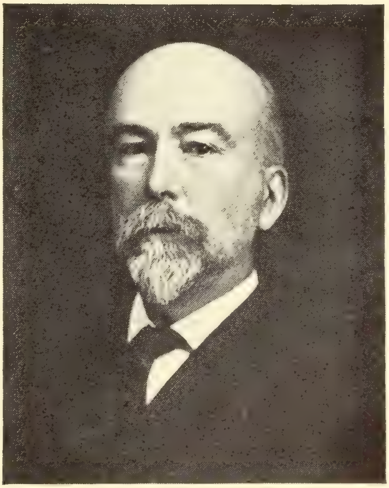


James Hall.

Ferdinand Zirkel.



Thomas Chrowder Chamberlin.



William Morris Davis.

world is like an onion to which successive layers have been added. He conceived of a primeval ocean completely enveloping the earth. From this shell of water were precipitated first the granites and associated greenstones, hornblende schists and porphyries, then slates and graywackes, followed in turn by limestone, coal, basalt, and ores; by sand, clay, soapstone, and finally by volcanic ash, some lavas, and jasper. Obviously, all igneous and metamorphic rocks found place with the sediments, for there was no place in this scheme for igneous activity, nor for structural changes in the earth's crust. To Werner volcanoes were "burning mountains"—the evidence of spontaneous combustion of buried beds of coal precipitated by an ancient sea. To him the world is the handiwork of Neptune; Pluto was disregarded. In spite of fundamental errors, Werner's teachings were dominant to the close of the eighteenth century, and in the early nineteenth century had the backing of leading scholars of Europe, and guided the work of Maclure, Eaton, and Silliman, the first American geologists. Only after a contest lasting for two decades did the opponents of the Wernerian School succeed in establishing the difference between igneous masses and sedimentary rocks in the geological series.

This prolonged controversy greatly stimulated observation and encouraged attempts at subdivision of stratified rocks which, however, showed little improvement over the work of Arduino and Füchsel. Progress depended on the development of new methods. The man and the method appeared in an unexpected place. William Smith, a civil engineer (1769-1838), had been quietly at work in all parts of England noting the position, extent, and composition of sedimentary rocks, collecting fossils from each stratum, and recording his observations on colored geological maps and sections. As part of his daily routine Smith noted that certain fossils reappear in the same beds at different localities and that each fossil species is

entombed in a definite formation. From this he drew the obvious inference that sedimentary formations may be recognized by their fossil content, and showed that one succession of sediments extends across England from south to east. In this matter-of-fact way the sure foundations of modern stratigraphy were laid; a modest lover of nature had found the way to read the history of the earth—one of the truly great contributions to science. Before William Smith, stratigraphic position and geologic age were based on chemical and mineralogical composition and attitude of rocks; fossils were incidental. Since his day fossils are the final court of appeal for questions of time and order of succession, and correlation of widely separated beds. The adequacy of Smith's methods was amply demonstrated in Conybeare and Phillips' *Outlines of the Geology of England and Wales* (1822)[46] and with the wide distribution of Lyell's famous *Principles of Geology* (1830-1833) came universal recognition of the fact that fossils provided the surest means for comparative study of sedimentary rocks.

Primitive, Transition, Secondary, Tertiary—the recognized subdivisions of the first quarter of the nineteenth century—gradually gave way to the ages and systems of the modern time-scale. In 1830 the three divisions of the Tertiary based on relative percentage of living species were established by Deshayes after a comparative study of the Tertiary rocks of England, France, Belgium, Poland, Hungary, and Italy. Lyell (1833) gave them the names now in use: Eocene, Miocene, Pliocene, and later added the term Pleistocene for the most recent alluvium and for the deposits now classed as glacial drift. The equivalents of certain English formations described by Smith were recognized in the Jura Mountains and in 1829

[46] Conybeare and Phillips' Outlines of the Geology of England and Wales was the first widely used treatise in the English language.

given the name Jurassic. With the addition of Triassic in 1834, the earlier "Secondary Class" became Triassic, Jurassic, and Cretaceous periods of Mesozoic (medieval) time. The analyses of the "Transition Class" of Werner and his contemporaries began with setting limits to the Carboniferous (1822) and continued through the establishment by English workers of the Cambrian (1835), the Silurian (1835), the Devonian (1839), and the Permian (1841) as periods of Paleozoic time. Even the "Primitive or Primary Class," supposed by the earlier stratigraphers to be the veritable bed-rock of the earth, was resolved by Logan into Huronian (1855) and Laurentian (1854) systems as periods of Archæan (Pre-Cambrian) time. It thus appears that during the forty years following the publication of Smith's geological memoir, English geologists had developed a time-scale by which the relative age of all the sedimentary and igneous rocks of the world could be measured. (See, Terms of the Geologic Column, Appendix III.)

Stratigraphic research during the second half of the nineteenth century has added volumes to the history of the earth. The increase in the number of gathered fossils from thousands to tens of thousands permits closer discrimination of horizons and with added knowledge of the breaks in the sedimentary record has led to a recognition of subdivisions in the Silurian, Carboniferous, and Cretaceous. By far the greatest contributions during the past half-century came from America. Through state and federal surveys,[47] and university activities, the condition of the earth during Cretaceous, Triassic, and Carboniferous times has been written into the record, and the work of James Hall[48] and his associates has made the stratified rocks of New York State the standard Paleozoic section for

[47] Government Geological Surveys, in A Century of Science in America, E. S. Dana, Editor, 1918.

[48] Zittel, Karl von, History of Geology and Paleontology, 1901.

the world. American stratigraphers like American paleontologists have advanced from learners to teachers.

During the past quarter-century attention has been directed to determining the physical conditions surrounding the deposition of sediments with a view to picturing more clearly the distribution of seas and lands, of streams and mountains, and separating areas of erosion from regions of deposition. The history of climates is also receiving attention and one of the most striking results of modern methods is the proof of glacial conditions not only in the Pleistocene but in the Permian of India, Africa, Brazil, Australia, and Massachusetts, and even among the oldest rocks of China, Norway, and Canada.

It is thus seen that fossils in a modern sense are more than proofs of evolution and more than markers which indicate relative age. They aid in writing the physical geography of the time in which they flourished.

If the record were complete enough it should be possible to locate the seas and lands, the lakes and rivers, reconstruct the mountains and plains, and restore the inhabitants of each geological period. Even with the meager fossil record, geologists are drawing coast lines of the earliest lands, pointing out deserts where rainfall is now abundant, and marking ancient tropical seas where cold winters now prevail. One of the most promising developments of the twentieth century is the preparation of physical geographies of important geological eras under the joint authorship of stratigraphers, paleontologists, and physiographers.[49]

Age of the Earth

The attractive myths of earth origin formulated by most uncivilized races wisely refrain from giving quantitative values to the expression "long ago." The philosophers of India re-

[49] Schuchert, Charles, The Progress of Historical Geology in North America, in A Century of Science in America, E. S. Dana, Editor, 1918.

garded the earth as eternal; the Chaldeans set 2,150,000 years as the age of the earth; Zoroaster was satisfied with 12,000 years; and with the establishment of Christianity in Europe, the Hebrew chronology prevailed and the limiting dates of earth history rested firmly on the recorded teachings of Moses. The views of the Christian world well into the nineteenth century were fairly represented by Bishop Ussher, who in 1650 fixed the date of the creation of the earth at 4004 B. C. Strangely enough this figure, founded on no facts and no arguments, rose to the dignity of a doctrine. For two hundred years it appeared on the margin of our English Bibles and was the test of orthodoxy. Even today this date or the corresponding Byzantine date 5509 B. C. is accepted by half of the Christian world. Under the influence of these ideas geologists up to the beginning of the nineteenth century felt compelled to squeeze all geological history into six or seven thousand years. This severe restriction could be harmonized with the growing body of geological fact only by the formulation of extraordinary hypotheses, a state of affairs that led to the magnification of Noah's flood and similar catastrophes as the all-powerful agents in molding the surface of the earth.

The scientific world was released from this thraldom by the bold teachings of Hutton that the present slow rate of geological processes must have been the rule since the dawn of geological history. No wonder that this view encountered opposition; it appeared to shake the very foundations of Christianity. The adherents to the established church chronology had scarcely recovered their breath when Darwin's *Origin of Species* brought from the biological realm data in support of the physical evidence developed by Hutton, Lyell, and others. The theory of evolution obviously demanded enormous drafts on time and was utterly inconsistent with previously accepted views. By the third quarter of the nineteenth century the conclusions of geologists and paleontologists had become too well

grounded to permit of substantial modification, but happily the first three words of the Bible, "In the beginning," and the "days" of creation were subject to new interpretations and the smoke of battle cleared away.

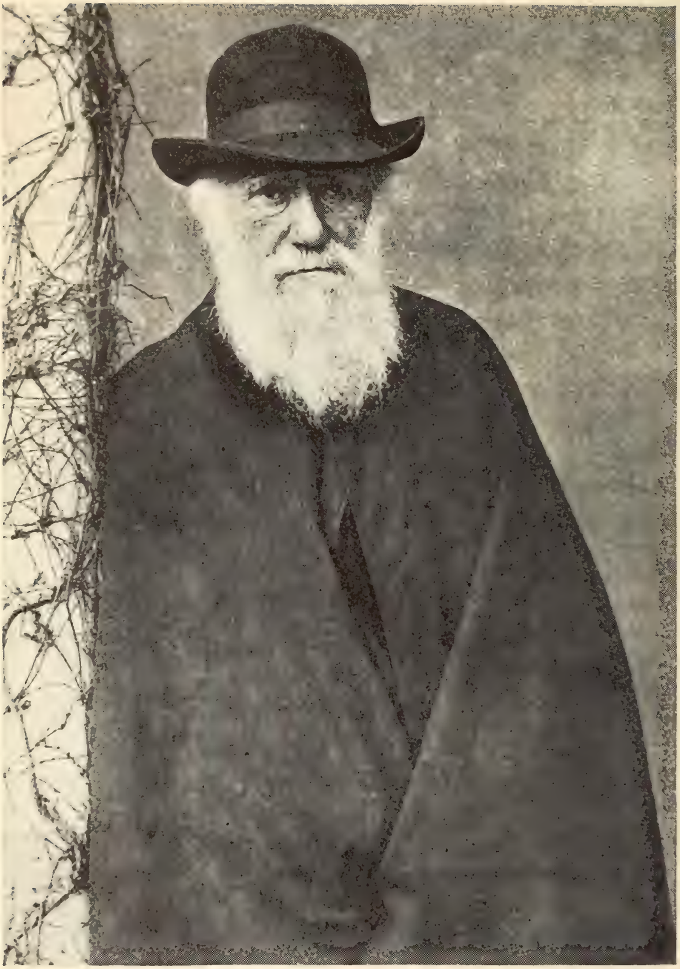
During the last half of the nineteenth century the advocates of a very ancient earth found themselves out of accord with the teachings of physics. Under the leadership of Lord Kelvin, mathematical proof was presented that the sun could not have been giving out heat for more than 100,000,000 years, perhaps only 40,000,000, and since the sun must have been producing heat for untold millions of years before life could have existed on the earth, only 10,000,000 to 20,000,000 years could be allowed for geological history. This amount of time is altogether too short for known geologic processes and for the evolution of living forms. When it is realized that the Cretaceous period alone may have had a duration equal to that allowed by Kelvin for all geologic time, the inadequacy of the physical estimates is apparent.

Though viewed with suspicion, the physical evidence appeared for a time irrefutable. Darwin was led to abandon his figures and some geologists undertook to speed up geological processes. In 1895 a re-examination of the physical data by Professor Perry revealed the weakness of Kelvin's arguments and modern students of radioactivity give the geologists not only the one or two hundred millions of years for which they have been contending, but allow 185,000,000 years since Carboniferous time and more than a billion years since the earth's first rocks were formed.[50]

The history of the earth as written during the past century is a fascinating story which has profoundly affected the world's thinking. Some chapters are complete, some need revision, many remain to be written. The interior of the earth and half the surface of the earth await geological exploration; the

[50] Holmes, Arthur, Age of the Earth, 1912.

mechanics of earth movements are not understood; the causes of variation in climate are imperfectly known; and the origin of life on the earth is shrouded in mystery. The chief problems awaiting solution call for assistance from chemistry, physics, biology, and astronomy, and further advance involves sympathetic co-operation.



CHARLES DARWIN

CHAPTER VI

BIOLOGY

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SOME practical acquaintance with plants and animals undoubtedly formed the chief content of the mental equipment of prehistoric man, and a considerable knowledge of agriculture and medicine was possessed by the Egyptians and Babylonians nearly 5000 years ago. So biology has a very ancient pedigree. But biology as the science of life—the study of living phenomena for their own sake, in which emphasis is shifted from the practical to the philosophical—really begins with the Greeks, and reaches *per saltum* a height which was not surpassed, indeed not again attained, for nearly twenty centuries.

Science, transported to Greece from the South and East, fell upon fertile soil, and in the hands of the Hellenic natural philosophers was organized into coherent systems through the realization that nature works by fixed laws—a conception foreign to the Oriental mind, and the corner-stone of all future work because it gave purpose to personal scientific investigation. This attitude of approach is largely responsible for the transformation of the Greek scientific heritage from a collectivistic to an eponymous product.[1] It is not an exaggeration to say that to all intents and purposes the Greeks laid the foundations of the chief subdivision of natural science and,

[1] Clodd, E., Pioneers of Evolution, 2d ed., 1907, pp. 29-32; Singer, C., Studies in the History and Method of Science, 1917.

specifically, created biology, though the term biology was first used by Lamarck and Treviranus at the beginning of the nineteenth century.[2]

Aristotle (384-322 B. C.), the most famous pupil of Plato and dissenter from the Platonic School, represents the high-water mark of the Greek students of nature and is justly called the Father of Natural History. Aristotle's contributions to biology are manifold. He took a broad survey of the existing facts and welded them into a science by relying, to a considerable extent, on the direct study of organisms and by insisting that the only true path of advance lay in accurate observation and description. But mere observation without interpretation is not science. Aristotle's generalizations—his elaboration of broad philosophical conceptions of organisms—give to his biological works their perennial significance. Among the facts and supposed facts there are interspersed questions, answers, theories which involve a recognition and remarkable grasp of fundamental biological problems; though of course there are many crudities because adequate apparatus and biological technique were of the distant future. A study of Aristotle's works shows ancient pedigrees for some of the most 'modern' questions of biology, though it is undoubtedly true, as Sachs insists, that one must continually inhibit the tendency to read the present viewpoint into the past, and not assign to earlier writers merits which, if they were alive, they themselves would not claim.

We have not mentioned a single discovery made by Aristotle—and with purpose. Aristotle's position as the founder of biology rests chiefly on his viewpoint and his methods. Plato relied on intuition as the basis of knowledge. Aristotle emphasized observation and induction, insisting that errors arise not from the false testimony of our sense organs but from false

[2] Lamarck, Hydrogéologie, 1802; Treviranus, G. R., Biologie, oder Philosophie der lebenden Natur für Naturforscher und Aerzte, 1802-1822.

interpretations of the data they afford. "We must not accept a general principle from logic only, but must prove its application to each fact; for it is in facts that we must seek general principles, and these must always accord with facts from which induction is the pathway to general laws."[3] But it is not to be imagined that Aristotle always followed his own advice; few great men do—"no pilot can explore unsurveyed channels without a confidence which sometimes leads to disaster." It must be admitted that Aristotle frequently lapsed into unbridled speculation which tended to obscure the methods that time has shown produce the most enduring results, though, as Huxley has well said, "It is a favorite popular delusion that the scientific enquirer is under a sort of moral obligation to abstain from going beyond that generalization of observed facts which is absurdly called 'Baconian' induction. But any one who is practically acquainted with scientific work is aware that those who refuse to go beyond fact, rarely get as far as fact; and any one who has studied the history of science knows that almost every step therein has been made by the 'Anticipation of Nature,' that is, by the invention of hypotheses, which, though verifiable, often had very little foundation to start with; and not infrequently, in spite of a long career of usefulness, turned out to be wholly erroneous in the long run."[4] As von Baer insisted, the method of science is not peculiar to it, but only a perfected application of our human resources of observation and reflection.

While Aristotle's biological investigations were devoted chiefly to animals, his pupil and co-worker, Theophrastus

[3] Aristotle, History of Animals, I, 6; Osborn, H. F., From the Greeks to Darwin, 1894, pp. 16-17, 47; Huxley, T. H., On Certain Errors Respecting the Heart Attributed to Aristotle, 1879 (Coll. Sci. Memoirs, 4, pp. 380-392); Lewes, G. H., Aristotle, a Chapter in the History of Science, 1864, pp. 108-113; Jones, T. E., Aristotle's Researches in Natural Science, 1912; Whewell, W., The Philosophy of Discovery, 1860.

[4] Huxley, T. H., The Progress of Science, 1887 (Coll. Essays, vol. 1, p. 62).

(370-286 B. C.), made profound studies on plants, and the list of botanical facts which he observed and in many cases discovered includes nearly all the rudiments of scientific botany. It is a remarkable fact that many details in plant anatomy which were figured by the pioneers with the microscope are to be found in the pages of Theophrastus.[5] He not only laid the foundations of botany, but also gave suggestions of much of the superstructure; an achievement which entitles him to rank as "the first of real botanists in point of time."[6]

With the Greeks, then, biology emerged from the shadows of the past and took concrete form—a fact which apparently the discerning mind of Aristotle appreciated since, though frequently referring to the ancients, he wrote:

> I found no basis prepared; no models to copy. . . . Mine is the first step, and therefore a small one, though worked out with much thought and hard labor. It must be looked at as a first step and judged with indulgence.

Before leaving the Greeks we must mention Hippocrates (460-370 B. C.), the Father of Medicine. Writing a generation before Aristotle, at the height of the Age of Pericles, Hippocrates crystallized the knowledge of medicine into a science, dissociated it from philosophy, and gave to physicians "the highest moral inspiration they have." "To him medicine owes the art of clinical inspection and observation, and he is, above all, the exemplar of that flexible, critical, well-poised attitude of mind, ever on the lookout for sources of error, which is the very essence of the scientific spirit. . . . The revival of the Hippocratic methods in the seventeenth century and their triumphant vindication by the concerted scientific movement of the nineteenth, is the whole history of internal medicine."[7]

[5] Greene, E. L., Landmarks of Botanical History, 1909, pp. 52, 53, 140-142.
[6] Haller, A., Bibliotheca Botanica, I, 31.
[7] Garrison, F. H., History of Medicine, 2d ed., 1917, p. 82.

Medicine, the most important aspect of applied biology, is the foster parent of zoology and botany, since a large proportion of biological advances have been the work of physicians. Until relatively recently the schools of medicine afforded the only training, and the practice of medicine the chief livelihood for men especially interested in general biological problems.[8] The history of medicine and of biology as a so-called pure science are so inextricably interwoven that the consideration of one involves that of the other. Indeed, the physicians form the only bond of continuity in biological history between Greece and Rome. The chief interest of the Romans lay in technology, and therefore it is natural that the practical advantages to be gained should ensure the advance of medicine.[9] As it happens, however, two Greek physicians were destined to have the most influence: Dioscorides (*c.* 64 A. D.), an army surgeon under Nero, and Galen (131-201 A. D.), physician to the Emperor Marcus Aurelius and his son, Commodus.

Just as Theophrastus established botany as a pure science, so Dioscorides was the originator of the pharmacopœia, writing, as he did, not only a work which was the first one on medical botany, but one which, gaining authority with age, was the sole standard 'botany' for fifteen centuries. Theophrastus was long overshadowed. Most of the botanical writings up to the seventeenth century were annotations on the text of Dioscorides.[10]

Galen was the most famous physician of the Roman Empire and his voluminous works represent both the depository for the anatomical and physiological knowledge of his predecessors, rectified and worked over into a system, and a large amount of original investigation. Galen was a practical anato-

[8] Huxley, T. H., The Connection of the Biological Sciences with Medicine, Nature, 24, 1881, pp. 342-346; also in Coll. Essays.
[9] Libby, W., An Introduction to the History of Science, 1917, Chapter 3.
[10] Greene, *op. cit.*, pp. 151-154.

mist who described from dissections and insisted on the importance of vivisection and experiment, and therefore he may be considered the first experimental physiologist and the founder of experimental medicine. Galen gave to medicine its standard anatomy and physiology for fifteen centuries.[11]

Any consideration of the biological science of Rome would be incomplete without a reference to the vast compilation of fact and fiction, indiscriminately mingled, made by Pliny the Elder (23-79). It was beside the path of biological advance, but long the recognized "Natural History," passing through some eighty editions after the invention of printing. Its prestige was largely due to the fact that it was written in Latin, whereas the great works on biological subjects were in Greek.[12]

For all practical purposes we may consider that biology at the decline of the Roman Empire was represented in the works of Aristotle, Theophrastus, Dioscorides, Galen, and Pliny. Even these exerted little influence during the Middle Ages, being saved from total loss for future generations chiefly by Arabian scientists, and in the monasteries of Italy and Britain. We cannot pause to consider the various causes which resulted in the almost complete break in the continuity of learning in general and science in particular during the dormant period in western Europe. Suffice it to say that contributing factors were wars and rumors of wars, the destruction of the libraries of Alexandria, the antagonism of Christian and pagan ideals, and the emphasis by the Church, which held the gates of learning, of the written word in place of observation of nature as it is. To a very large extent "truth and science came to mean simply that which was written, and inquiry became mere interpretation," though recent historical studies are revealing

[11] Foster, M., Lectures on the History of Physiology, 1901; Garrison, *op. cit.*, pp. 97-101; Verworn, M., General Physiology, English trans., 1899, pp. 8-11.

[12] Hulme, F. E., Natural History Lore and Legend, 1895, pp. 20-29; Greene, *op. cit.*, pp. 155-159.

medieval scientific manuscripts which may necessitate a reappraisal of the period.[13]

In so far as science reached the people in general, it was almost solely from small compilations of corrupt texts of ancient authors interspersed with anecdotes and fables. Quite characteristic of the times is the oft-quoted *Physiologus,*[14] found in many forms and languages, that evolved into a collection of natural history stories in which the centaur and phœnix take their place with the frog and crow in affording allegorical illustrations of texts and in pointing out more or less evident morals. The line of demarcation between the *Physiologus* and the *Bestiaries* is ill defined, while the remnants of the latter are incorporated in the early works of the Renaissance encyclopædists.[15]

The scientific Renaissance may be said to owe its origin to the revival of classical learning and to the translation and study of the writings of Aristotle and others which had been under eclipse for a thousand years. These were so superior to the existing science that, in accord with the spirit of the time, Aristotle and Galen became the bible of biology. The first works were merely commentaries on the classical authors, but as time went on more and more new observations were interspersed with the old until elaborate and voluminous treatises describing all known forms of plants and animals were produced. In short, the climax of the scientific Renaissance involved a turning away from the authority of Aristotle and an adoption of the Aristotelian method of observation and induction.

[13] White, A. D., History of the Warfare of Science with Theology in Christendom, 1898; Clodd, *op. cit.,* p. 34; Russell, *op. cit.,* pp. 124 *et seq.;* Singer, D. W., Scientific Manuscripts in the British Isles before the Sixteenth Century, 1919.

[14] White, *op. cit.;* Lauchert, F., Geschichte des Physiologus, 1889; Thorndike, L., History of Magic and Experimental Science, 1923, 1, pp. 497-503.

[15] Hulme, *op. cit.,* pp. 31, 50.

Botany was the first to show visible signs of the awakening, probably because of the dependence of medicine on plant products. "All physicians professed to be botanists and every botanist was thought fit to practice medicine." The multiform *Ortus Sanitatis,* a sort of combined 'botany' and Bestiary, gave place to the Herbals.[16] At the hands of the herbalists of the sixteenth century, such as Brunfels (1464-1534), Fuchs (1501-1566), Tragus (1498-1554), and Valerius Cordus (1515-1544) of Germany, Mattioli (1501-1577) of Italy, Dodoens (1507-1585) of Belgium, and Turner (1510-1568) of England, is traceable the evolution of plant description and classification from mere annotations on Dioscorides to well-illustrated manuals of the flora of western Europe, while Aristotelian influence is emphasized in the *De Plantis* of Cesalpino (1519-1603) of Italy. But Valerius Cordus was more than 'herbalist' implies, for this youthful genius "first taught men to cease from dependence on the poor descriptions of the ancients and to describe plants anew from nature," and so holds a somewhat similar relationship to the development of botany that Vesalius does to human anatomy.[17]

During the same century zoology made abortive attempts to emerge as a science, but the less immediate utility of the subject combined with the difficulty of collecting material and therefore the necessity of considerable dependence on travelers' tales all contributed to retard its advance.

One group of naturalists, the encyclopædists, so called from their endeavor to gather all possible information of living things, attempted the impossible. Gleaning from the ancients and adding such materials as they could collect led to the production of huge books of fact and fancy whose value bore no just proportion to the amount of labor involved, even in the

[16] Arber, A., Herbals; their Origin and Evolution. A Chapter in the History of Botany, 1912.

[17] Greene, *op. cit.,* pp. 164 *et seq.*

case of the best—Gesner's *Historia Animalium,* which appeared volume by volume between 1551 and 1587, and comprised some 4500 folio pages of text and wood cuts.[18]

Although Gesner (1516-1565) was without doubt the most learned naturalist of the period and perhaps the best zoologist that had appeared since Aristotle, the direct path to progress was blazed by men whose plans were less ambitious than those of the encyclopædists. Thus, contemporaries of Gesner, men who were befriended by him, such as Rondelet (1507-1566) who gave descriptions of the fishes of the Mediterranean based for the most part on his own observations, and Belon (1517-1564) who illustrated the fishes and birds which he saw in France and the Levant, really instituted the zoological monograph which has proved the productive method of biological study.[19]

Even while the herbalists, encyclopædists, and monographers were at work in natural history, making brave attempts to develop the powers of independent judgment which were oppressed to such an extent during the Middle Ages that the very activity of the senses seemed stunted, the emancipator of biology from the thraldom of the ancients appeared in the Belgian anatomist, Vesalius (1514-1564). Disgusted with the anatomy of the time, which consisted almost solely in interpreting the works of Galen by reference to crude dissections made by barbers' assistants, Vesalius set his hand to the task of placing human anatomy on the firm basis of exact observation, and his great work, *De Humani Corporis Fabrica,* makes the year 1543 the dividing line between ancient and modern anatomy.[20] Galen's similar attempt failed because his followers made a bible of his work; but with Vesalius the time was op-

[18] Miall, L. C., The Early Naturalists, Their Lives and Work, 1912, pp. 47-50.
[19] Miall, *op. cit.,* pp. 40-47.
[20] Stirling, W., Some Apostles of Physiology, 1902, pp. 2-5; Foster, M., *op. cit.,* p. 2.

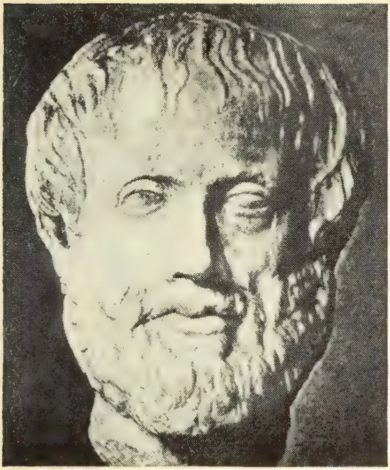
portune and, in spite of the opposition of his former teacher Jacobus Sylvius (1478-1555), and his pupil Columbus (1516-1557), thenceforth anatomical as well as biological investigation in general broke away from the yoke of authority and men began to trust their own eyes. His successor at Padua, Falloppius (1523-1563), says that Vesalius "so shewed me the true path of inquiry that I was able to walk along it still farther than had been done before."

The work of Vesalius is on anatomy, and physiology is treated somewhat incidentally, though it is evident that he was no better satisfied with Galenic physiology than with Galenic anatomy. The complementary work on the side of function came in 1628 with the publication of Harvey's tract, *Exercitatio Anatomica de Motu Cordis et Sanguinis in Animalibus.* No rational conception of the economy of the animal organism was possible under the influence of the Galenic system, and it remained for Harvey (1578-1657) to demonstrate by a series of experiments, logically planned and ingeniously executed, that the blood flows in a circle from heart back to heart again, and thus to supply the groundwork for a proper understanding of the dynamics of the organism as a whole. A new picture of the function of the blood was presented which quickly led to the discovery of the lymphatic system, and gave content to the study of the nutrition of the body.[21]

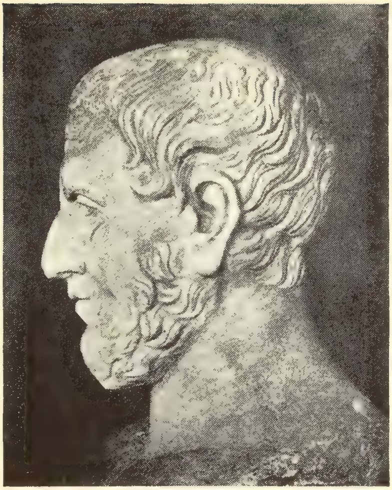
Harvey's use of distinctively quantitative factors is so important in its establishment of the experimental method in biology that his own statement is of great historical interest:

> I frequently and seriously bethought me, and long revolved in my mind, what might be the quantity of blood which was transmitted, in how short a time its passage might be effected, and the like; and not finding it possible that this could be supplied by the juices of the in-

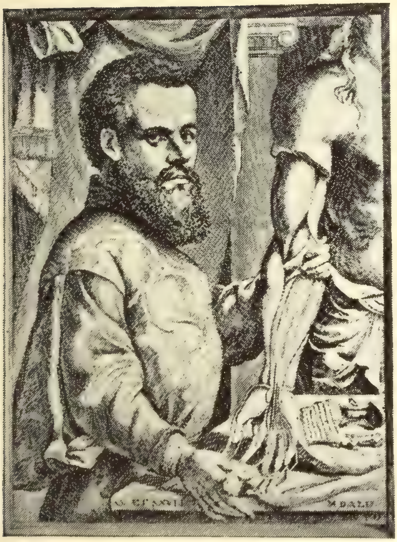
[21] Curtis, J. G., Harvey's Views on the Use and Circulation of the Blood, 1915; Huxley, T. H., William Harvey, Fortnightly Review, 23, 1878 (also Coll. Sci. Memoirs, 4, p. 319).



Aristotle.



Theophrastus.



Andreas Vesalius.

William Harvey.

gested aliment without the veins on the one hand becoming drained, and the arteries on the other hand getting ruptured through the excessive charge of blood, unless the blood should somehow find its way from the arteries into the veins, and so return to the right side of the heart; I began to think whether there might not be a motion, as it were, in a circle. Now this I afterwards found to be true; and I finally saw that the blood, forced by the action of the left ventricle into the arteries, was distributed to the body at large, and its several parts, in the same manner as it is sent through the lungs, impelled by the right ventricle into the pulmonary artery, and that it then passed through the veins and along the vena cava, and so round to the left ventricle in the manner already indicated. Which motion we may be allowed to call circular.[22]

With the work of Cordus, Vesalius, and Harvey, biologists had again laid hold of the great scientific tools—observation, experiment, induction—which since have not slipped from their grasp.

The Microscopists

Even while the marshaling of accurate descriptions of plants and animals was getting under way, and the study of macroscopic anatomy and physiology was making rapid strides forward, an event occurred which was destined to make possible modern biology. This was the invention, probably by Roger Bacon (1214-1294), of convergent, crystal lenses which he says are "useful to old men and to those whose sight is weakened, for by this means they will be able to see the letters sufficiently enlarged, however small they may be." Thus from the principle of spectacles, more powerful lenses—'simple' microscopes—were developed. The use of a system of lenses for the magnification of small objects near at hand appears to have occurred to Galileo (1564-1642) from the recently invented telescope, and thus the 'compound' microscope began its long developmental history. By the end of the century sim-

[22] Harvey, De Motu Cordis et Sanguinis, English trans. by R. Willis, 1848. (See reprint in Everyman's Library, pp. 55-56.)

ple and compound microscopes were being made by opticians in the leading European centers.[23]

The earliest clear appreciation of the importance of studying living nature with instruments which increase the powers of the senses in general and of vision in particular, is found in a remarkable book, the *Micrographia* of Robert Hooke (1635-1703), published by the Royal Society of London in 1665, which is a demonstration of the advantages to be gained by the use of artificial devices of precision.

> The next care to be taken, in respect to the senses, is a supplying of their infirmities with instruments, and, as it were, the adding of artificial organs to the natural; this in one of them has been of late years accomplished with prodigious benefit to all sorts of useful knowledge, by the invention of optical glasses. . . . It seems not improbable, but that by these helps the subtiliety of the composition of bodies, the structure of their parts, the various texture of their matter, the instruments and manner of their inward motions, and all the other possible appearances of things, may come to be more fully discovered. . . .[24]

Although the book is replete with singular anticipations of the discoveries and inventions of other workers in various branches of science, the biologist's interest is chiefly in Hooke's application of his improved compound microscope to the study of plants and animals, which paved the way for the more special, profound, and methodical studies of the contemporary students of nature. In the *Micrographia* are clearly described and figured for the first time the "little boxes or cells"[25] of organic structure, and his use of the word 'cell' is responsible for its application to the protoplasmic units of modern biology. It is fair to say that the influence of the *Micrographia* permeated the sciences in various directions and the illustrations of microscopic objects were copied for nearly two centuries.[26]

[23] Bacon, R., Opus Major, 1276; Miall, *op. cit.*, p. 136.
[24] Micrographia, preface.
[25] Micrographia, Observation XVIII, pp. 112-116.
[26] Woodruff, L. L., Hooke's Micrographia, American Naturalist, 53, 1919.

The *Micrographia* was a mere incident in the varied interests of Hooke, while Leeuwenhoek (1632-1723) spent a long life in studying nearly everything which he could bring within the scope of his simple lenses. Fascinated with the "world of the infinitely little," with a virgin field before him, and no literature on the subject to divert his energies, he was able year after year to send letters to learned academies, chiefly the Royal Society of London, describing what of necessity were discoveries. He saw the bacteria—he is the first bacteriologist, the protozoa—he is the first protozoologist, yeast cells, rotifers, hydra; but the list is too long.[27] However, all of Leeuwenhoek's work is by no means desultory. He displayed much ingenuity in studying the flow of blood through the capillaries of the web of the frog's foot and bat's wing, the viviparous reproduction in aphids, the development of fleas, the desiccation of rotifers. And all the time he was looking for evidence against the idea of spontaneous generation, being convinced "it is fully proved that no living creature is produced by corruption or putrefaction."[28] But Leeuwenhoek's contribution which attracted the most interest was his description of spermatozoa. Brought to his attention by a young physician, Hamm, Leeuwenhoek transmitted the discovery to the Royal Society. His imagination, however, outstripped his observations and he thought he saw evidence of a homunculus within the spermatozoon. So he came to regard the sperm as the true germ which had only to be hatched, as it were, by the female. He was thus the first of the school of 'spermists,' which opposed the idea of the 'ovists' that all is preformed in the egg.[29]

The patience of Leeuwenhoek would have been strained to the breaking point by the studies on insect anatomy made by

[27] Miall, *op. cit.,* pp. 200-223; Richardson, B. W., Disciples of Æsculapius, 1900.

[28] Select Works of A. van Leeuwenhoek, edited by S. Hoole, 1800-1807.

[29] Phil. Trans. Royal Soc., 142, 1678.

Swammerdam (1637-1680) and eventually brought together in his *Biblia Naturæ*. Instigated largely by the desire to refute the current notion, supported by certain statements of the great Harvey, that insects and similar lower animals are merely masses of organic matter which have been molded, as it were, into a definite form, and are without complicated internal organs, Swammerdam spent his life in studies on their structure and life histories.[30] Revealing as he did, by the most delicate technique in dissection, the finest details observable with his lenses, Swammerdam not only set a standard for minute anatomy which, with that of his contemporary Malpighi, was not surpassed until the work of Lyonet (1707-1789) and others nearly a century later, but also dissipated, for all time, the conception of simplicity of structure in the lower animals. Swammerdam thus quite naturally added one more argument to those of Redi and others against spontaneous generation:

> That vulgar opinion, . . . which ascribes birth and growth of animals to putrefaction and chance, is diametrically opposite to sound reason. . . . In the smallest animals we constantly everywhere find as much order, contrivance, beauty, wisdom, and omnipotence in the Great Architect, as are shown in the viscera of the largest animals. For to these greater animals all others, however minute, are similar in the great respects of brain, nerves, muscles, heart, stomach, intestines, and parts subservient to generation, and to every other useful purpose; so that one might in a manner affirm, that God has created but one animal, though divided into an infinite number of kinds or species, differing from each other in the figures and inflexions, and extensions of their limbs, as likewise in their dispositions, food and manner of living.[31]

Contemporaries of Hooke, Leeuwenhoek, and Swammerdam were two men who may be considered as the pioneer histologists—Malpighi of Bologna and Grew of London. Grew

[30] Boerhaave, H., Life of Swammerdam (preface to the Biblia Naturæ); Miall, *op. cit.*, pp. 174-199. Also Miall's History of Biology, 1911.

[31] Biblia Naturæ, English trans., edited by John Hill, 1758, part 2, p. 71.

(1641-1712) devoted all his attention to plant structure, while Malpighi, in addition to botanical studies which paralleled Grew's, made elaborate investigations on animals.

The versatility as well as the genius of Malpighi (1628-1694) is illustrated by his studies on the anatomy of plants, the function of leaves, the development of the plant embryo, the embryology of the chick, the anatomy of the silkworm, the structure of glands.[32] Master of morphology but with prime interest in physiology, his lasting contribution lies in his dependence on the microscope for the elucidation of problems where structure and function, so to speak, merge. This is well illustrated by his ocular demonstration of the capillary circulation in the lungs, at once his first and greatest discovery and the first of prime importance ever made with a microscope—since it completed Harvey's work on the circulation of the blood. Malpighi wrote:

> I see with my own eyes a certain great thing. . . . It is clear to the senses that the blood flowed away along tortuous vessels and was not poured into spaces, but was always contained within tubules, and that its dispersion is due to the multiple winding of the vessels.[33]

The microscopists taken collectively created an epoch in the history of biology, so important is the lens for the advancement of the science.[34] Indeed, we find that, broadly speaking, its development along many lines during the eighteenth and particularly the nineteenth centuries has gone hand in hand with improvements in the compound microscope itself and in microscopical technique. Again, the microscopists in general and Malpighi in particular opened up so many new paths of advance that from this period on it is not possible, even in the most general survey, to discuss the development of biology as a whole. The composite picture must be formed by empha-

[32] Miall, *op. cit.*, p. 145.
[33] Foster, *op cit.*, p. 96.
[34] Sachs, History of Botany, English trans., 1890, pp. 220-222.

sizing and piecing together various lines of work, such as classification, comparative anatomy, embryology, physiology, genetics, and evolution.

Taxonomy

Classification has as its object the bringing together of things which are alike and the separating of those which are unlike. It is "discrimination, description, and illustration—the necessary census task which forms the groundwork on which great theories may be built up"[35]—a problem of no mean proportions when a conservative estimate today shows upwards of a million species of animals and plants, leaving out of account the myriads of forms represented only by fossil remains. Naturally the earliest classifications were utilitarian, or more or less physiological: edible and harmful, useful and useless, fish of the sea and beasts of the earth. But as knowledge increased, emphasis was shifted to the anatomical criterion of specific differences and thenceforth classification became at once an important aspect of natural history—a central thread both practical and theoretical. Practical, in that it involved the arranging of living forms so that a working catalog was formed which required nice anatomical discrimination, and therefore the amassing of a large body of facts concerning animals and plants. Theoretical, because in the process botanists and zoologists were impressed, almost unconsciously at first, with the 'affinity' of various types of animals and of plants and so were led to problems of their origin.

From Aristotle, who emphasized the grouping of organisms on the basis of structural similarities, we must pass over some seventeen centuries, in which the only work of interest was done by the herbalists and encyclopædists, to the time of Ray (1628-1705) of Cambridge. As a matter of fact, the Theophrastan classification of plants as trees, shrubs, and

[35] Praeger, R. L., in Oliver's Makers of British Botany, 1913, p. 220.

herbs persisted until the end of the seventeenth century. Previous to Ray the term 'species' was used somewhat indefinitely, and his chief contribution was to make the word more concrete by applying it solely to groups of similar individuals which exhibit constant characters from generation to generation. Covering, as Ray's labors did, the classification of both animals and plants, it is probably not an exaggeration to regard him as the seventeenth century precursor of the great Swedish taxonomist, Linnæus, for whom he paved the way.[36]

Like many another genius, Linnæus (1707-1778) was a product of his time and, perhaps, one of the very best examples of the fact that "the most original people are frequently those who are able to borrow the most freely"—to see a great deal in what to others appears commonplace. Linnæus was first and foremost a botanist. Garnering much of the best which the past had to offer in taxonomy, and bringing to bear on it his supreme talent for "classifying, coördinating, and subordinating," Linnæus gave botanical students at once a practical method of classification of flowering plants, based chiefly on the number and arrangement of the stamens. At the same time he insisted on brief descriptions and the scheme of giving each kind of organism a name composed of two words, in which the second word indicates the species and the first, the genus, a group of closely similar species. In short, to name an organism is to classify. Linnæus' success with botanical taxonomy led him to extend the principles to animals and even to the so-called mineral kingdom, the latter showing at a glance his lack of appreciation of any genetic relationship between species.[37]

Indeed, the terms genus and species to Linnæus expressed a transcendental affinity since he believed that species, genera,

[36] Vines, S. H., Robert Morrison and John Ray, in Oliver's Makers of British Botany, 1913, p. 9.

[37] Sachs, *op. cit.*, p. 108; Miall, History of Biology, 1911, p. 66.

and even higher groups represented distinct, consecutive thoughts of the Creator. Accordingly, the ultimate goal of taxonomy was to determine the so-called *scala naturæ.* This viewpoint is somewhat whimsically expressed by an old naturalist who, finding a beetle which did not seem to agree exactly with any species in his collection, solved the difficulty by crushing the unorthodox individual under his foot. Thus, Linnæus crystallized two dogmas—constancy and continuity of species—which permeated biology and reached, in slightly different form, their high-water mark, indeed a *reductio ad absurdum,* in Agassiz's *Essay on Classification* a century later—as fate would have it, just a year before Darwin's *Origin of Species*[38] appeared.

Though today Linnæus' conception of fixity has been replaced by modifiability of species, the affinity which he recognized and expressed in transcendental terms has given place to similarity based on descent, and his artificial classifications have been superseded by natural classifications, which express, or attempt to express, this genetic connection between species—nevertheless his greatest works, the *Systema Naturæ* and *Species Plantarum,* created an epoch in biological history, and are by common consent the base line of priority in zoological and botanical nomenclature.[39]

The aftermath of Linnæus' labors must be mentioned. Naturalists in general and botanists in particular were so captivated with the facility which the Linnæan system afforded for cataloging, that collecting and naming became a dominant note for nearly a century. The few who employed microscope and scalpel are outstanding figures on the path to progress. And further, botanists complacently allowed the Linnæan practical but artificial classification to divert temporarily their interest from the quest for a natural classification which had

[38] Miall, 1911, *op. cit.,* p. 157.
[39] Systema Naturæ, 1735, 10th ed., 1758; Species Plantarum, 1753.

been begun so propitiously with the work of Cesalpino, Jung (1587-1657), Ray, and Tournefort (1656-1708).[40]

Comparative Anatomy

The first step towards scientific classification was made, as we have seen, by Aristotle in emphasizing anatomical characters as taxonomic criteria, so that to all intents and purposes classification implies comparison of structural details. Indeed, Aristotle recognized the unity of structural plan throughout the chief animal groups, and in reference to man he says, "whatever parts a man has before, a quadruped has beneath; those that are behind in man form the quadruped's back." Not only did he appreciate homology, but also correlation of parts and division of labor in the economy of the animal body.[41] And Theophrastus approached plant morphology in the same philosophical spirit—witness his recognition of the flower as a metamorphosed leafy branch.[42] But it probably would be reading too much into the past to assign the origin of comparative anatomy of animals in the modern sense of the term to Greek, Roman, or early Renaissance science, since description rather than comparison was the keynote. The same may be said of the anatomical work of Vesalius, Harvey, and Malpighi, though the latter compared the microscopic structure of various organs, and in his *Anatomy of Plants,* which shares with Grew's *Anatomy* the honor of founding vegetable histology, emphasized the importance of the comparative method. Owing to the less marked structural differentiation of plants in comparison with animals, plant anatomy does not lend itself so readily to descriptive analysis and therefore an epoch in the

[40] Oliver, F. W., Makers of British Botany, 1913, pp. 39, 134, 193. For the point of view of the early part of the nineteenth century, *cf.* Swainson, W., On the Study of Natural History, 1834.

[41] Russell, E. S., Form and Function; A Contribution to the History of Animal Morphology, 1917, Chapter 1.

[42] Greene, *op. cit.*

study of comparative anatomy is less defined in botany than in the sister science. Accordingly both reason and expediency warrant confining our attention to the comparative anatomy of animals.

Probably the first consistent attempt to make a comparative study of the form and arrangements of the parts of animals is represented in a volume published in 1645 by Severinus (1580-1656) of Naples, in which he concluded that many vertebrates are constructed on the same plan as man, though Belon, nearly a century earlier, figured and compared the skeletons of bird and man side by side in the same posture, and as nearly as possible bone for bone.[43] Tyson (1650-1708) of Cambridge at the end of the seventeenth century definitely instituted the monographic treatment of comparative morphological problems in his study of the anatomy of man and monkeys.[44]

Comparative anatomy, however, as a really important aspect of biological work, in fact as a science in itself, was the result of the life work of Cuvier (1769-1832) of Paris during the first quarter of the last century. It is true that his immediate predecessors, such as John Hunter (1728-1793), the founder of the Hunterian Collection, the nucleus of the Anatomical Museum of the Royal College of Surgeons in London, Camper (1722-1789) of Groningen, and Vicq d'Azyr (1748-1794) of Paris, added synthesis to analysis and reached a broader viewpoint in anatomical study, but Cuvier's claim to fame rests on the remarkable breadth of his investigations—his grasp of the comparative anatomy of the whole series of animal forms.[45] And not content merely with the living, he made himself the first real master of the anatomy of fossil vertebrates and as such is the founder of vertebrate paleon-

[43] P. Belon, L'Histoire de la nature des Oyseaux, 1555; Miall, History of Biology, pp. 18-19.

[44] Tyson, E., Orang-Outang, sive Homo sylvestris, 1699; Garrison, *op. cit.*, p. 240.

[45] Russell, *op. cit.*, Chapter 3.

tology, while his contemporary, Lamarck, holds the same relation to invertebrate paleontology.[46]

Cuvier's position in the history of anatomy is largely due to his emphasizing, as Aristotle had done before him, the functional unity of organisms—that the interdependence of organs results from the interdependence of function and that structure and function are two aspects of the living machine which go hand in hand. Cuvier's famous principle of correlation—"Give me a tooth," said he, "and I will construct the whole animal"—is really an outcome of this viewpoint. Every change of function involves a change in structure and therefore, given extensive knowledge of function and of the interdependence of function and structure, it is possible to infer from the form of one organ that of most of the other organs of an animal. "In a word, the form of the tooth implies the form of the condyle; that of the shoulder blade that of the claws, just as the equation of a curve implies all its properties."

Although Cuvier undoubtedly allowed himself to exaggerate his guiding principle until it exceeded the bounds of facts, he was above all in his science and philosophy a hard-headed conservative and autocrat. He opposed with equal vigor the influence of the *Naturphilosophie* of Schelling and his school with its transcendental anatomy, Platonic archetypes and the like, as well as the evolutionary speculations of Lamarck and his school. From the vantage points of today we know that in one case he was right and in the other wrong—though, in so far as the facts then available, his opposition was justified in both cases.

Cuvier's immediate successors in France were Milne-Edwards (1800-1885) and Lacaze-Duthiers (1821-1901); in Germany, Meckel (1781-1833), Rathke (1793-1860), Mül-

[46] Huxley, T. H., The Rise and Progress of Paleontology, Nature, 24, 1881 (also Coll. Sci. Memoirs, 4); Marsh, O. C., History and Methods of Paleontological Discovery, Presidential address, Amer. Assn. Adv. Sci., 1879.

ler, and Gegenbaur (1826-1903); in England, Owen and Huxley, and in America, Agassiz (1807-1873), Cope (1840-1897), and Marsh (1831-1899). Among these, Owen (1804-1892) perhaps demands special mention. At once a peculiar combination of Cuvierian obstinacy in regard to facts and of transcendental imagination, Owen spent a long life dissecting with untiring patience and skill a remarkable series of animal types, as well as in reconstructing extinct forms from fossil remains. Aside from the facts accumulated, probably his greatest contribution was making concrete the distinction between homologous and analogous structures, which has been of the first importance in working out the pedigrees of plants as well as animals—though Owen himself took an enigmatical position in regard to organic evolution.[47]

Physiology

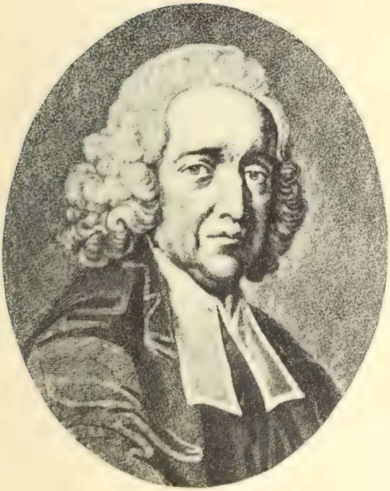
Anatomy emphasizes the static and physiology the kinetic aspect of the organism, though, as we have seen, structure without function is a lifeless subject and function without structure is an impossibility, since, in Huxley's happy phraseology, physiology is the mechanical, and he would now add, chemical engineering of the living organism.

Animal and plant physiology were discussed by Aristotle, but as might be expected, since physiology is more dependent than anatomy upon progress in other branches of science, with less happy results. Similarly, Galen was hampered in his attempt to make physiology a distinct department of learning based on a thorough study of anatomy, and the corner-stone of medicine. Like Aristotle he attempted to develop a picture of the *modus operandi* of the organism, and with such success that fate foisted it upon uncritical generations through fifteen cen-

[47] Life of Richard Owen, by his grandson, 1894, Vol. 2, pp. 89-96. Also, essay on Owen's Position in the History of Anatomical Science by T. H. Huxley, in above work.

Marcello Malpighi.

Antony van Leeuwenhoek.



Stephen Hales.

Albrecht von Haller.

turies. And the unfortunate fact was not that Galen's physiology and anatomy were largely incorrect, but that to question his authority was little less than sacrilege until the labors of Vesalius and Harvey brought a realization that Galen had not quite finished the work.[48]

Neither Vesalius nor Harvey made an attempt to explain the workings of the body by appeal to so-called physical and chemical laws; and for good reason. Chemistry had not yet thrown off the shackles of alchemy and taken its legitimate place among the elect sciences, while during Harvey's lifetime, under the influence of Galileo, the new physics arose. But by the end of the seventeenth century both physics and chemistry, aided by the philosophical systems of Bacon and Descartes, had forced their way into physiology and split it into two schools: the iatro-mechanical founded by Borelli (1608-1679), who by incisive physical methods attacked a long series of problems, frequently with brilliant results; and the iatro-chemical school, which developed from the influence of Franciscus Sylvius (1614-1672) as a teacher rather than as an investigator.[49]

This awakening brought a host of workers into the field and the harvest of the century was garnered and enriched by Haller (1708-1777), the "abyss of learning" of the time, in a comprehensive treatise which at once indicated the erudition and critical judgment of its author and established physiology as a distinct and important branch of biological science, rather than as a mere adjunct of medicine.[50] Great as was this contribution of Haller in crystallizing physiology and setting the dividing line between the old and the modern, unfortunately the weight of the author's authority was ranged in favor of two theories which were, in crude form, attracting the attention of

[48] Foster, *op. cit.,* p. 12.

[49] Foster, *op. cit.,* Chapters 3 and 6.

[50] Haller, Elementa Physiologiæ Corporis Humani, 1757.

biologists—the idea of special vital force and the preformation theory of development.

Perhaps the most significant lines of advance in Haller's century were in setting the physiology of nutrition and respiration—both of which waited upon the work of the chemists—well upon their way towards modern form. Réaumur (1683-1757) of Paris, and Spallanzani (1729-1799) of Pavia may be singled out for their exact studies of gastric digestion which, against the background of the pioneer work during the previous century by van Helmont (1577-1644), Jacobus Sylvius (1614-1672), Stensen (1638-1686), de Graaf (1641-1673), Peyer (1653-1712), and Brunner (1653-1727), established solution of the food as the main factor in digestion, though it was not clear how these changes differed from ordinary chemical ones. So physiologists of a vitalistic turn of mind cloaked their ignorance under the term "animalization," and left for eighteenth century investigators the establishment of the fact that food in passing along the digestive tract runs the gamut of a series of complex chemical substances, or enzymes, each of which has its part to play in putting the several constituents of the food into such a form that they can pass to the various cells of the body.[51]

On the side of respiration a somewhat closer approach was made towards a true understanding of the process, but there was a better foundation on which to build. The Galenic notion that respiration is a process of refrigeration—a getting rid of the innate heat of the heart and of fuliginous vapors—had been superseded, through the efforts of Harveyan experimentalists—the chemist Boyle (1627-1691), the versatile genius Hooke, the physician Lower (1631-1690), and the lawyer-chemist Mayow (1643-1679). The climax only awaited the overthrow of the Stahlian phlogiston theory, which presented

[51] Johnson, W. B., History of the Progress and Present State of Animal Chemistry, 1803.

an inverted picture of combustion, and the actual discovery of oxygen. This came in the work of Black (1728-1799), Priestley (1733-1804), Lavoisier (1743-1794), and Girtanner (1760-1800), which made it clear that the chemical changes taking place in respiration involve essentially a process of combustion, and it chiefly remained for later work to show that this takes place in the tissues rather than in the lungs.[52]

Enough perhaps has been said to indicate the trend of physiology away from the maze of Galenic spirits in which science lost itself, towards the modern atmosphere of science with its *working hypothesis* that life phenomena are an expression of a complex interaction of physico-chemical laws which do not differ fundamentally from the so-called laws operating in the inorganic world, and that the economy of the organism is in accord with the law of the conservation of energy—probably the most far-reaching generalization of science during the past century. Although it is difficult to discriminate, certainly the names of Liebig, Wöhler (1800-1882), the brothers Weber, Ludwig (1816-1895), Helmholtz (1821-1894), Müller (1801-1858), and Dubois-Reymond (1818-1896) in Germany; Dumas (1800-1884), Magendie (1783-1855) and Bernard (1813-1878) in France; Donders (1818-1889) in Holland; and Hall (1790-1857) in England were, individually and collectively, chiefly responsible for the reformation of physiology.[53]

Most of the foundation on which the physiology of animals rests today has been built up by work on vertebrates, though since the middle of the nineteenth century, when the versatile Müller showed the value of studying the physiology of higher and lower animals alike, the science of comparative physiology

[52] Loeb, J., Dynamics of Living Matter, p. 7; Hertwig, O., The Growth of Biology in the Nineteenth Century, Smithsonian Report, 1900, pp. 461-478.

[53] Verworn, M., General Physiology, English trans., 1899, pp. 16-20; Stirling, *op. cit.*, p. 106.

may be said to have been established.[54] Perhaps it is not an exaggeration to say that the tendency to focus evidence, in so far as possible, from all forms of life on general problems of function represents the present trend of physiological inquiry.

The less obvious structural and functional differentiation of plants retarded progress in plant physiology as it did in plant anatomy. Probably of most historical, and certainly of most general interest is the development of our knowledge of the nutrition of green plants.

Aristotle's theory that the food of plants is prepared for them in the ground was still prevalent at the end of the sixteenth century when Cesalpino, the most philosophic botanist of his day, thought that food enters and passes through vessels and fibers of plants much as oil in a lamp wick, and Jung conceded that plants are not mere passive absorbers of ready-made food, but possess the power of selecting from the soil the ingredients needed. But it was van Helmont, on the border line between alchemist and chemist, who precociously brought to bear the chemical point of view on animal physiology and made the first recorded experiment in plant nutrition. He planted a small tree in a large vessel and weighed it. Then after five years, during which time it had only been supplied with water, he found that it had increased some thirty-fold in weight and "not suspecting that the plant drew a great part of its materials from the air was forced to exaggerate the virtues of rain-water."[55] Malpighi, however, from his studies on plant histology, gave the first hint of the fact of supreme importance that the crude sap, which enters by the roots, is carried to the leaves where, by the action of sunlight, evaporation, and some sort of a fermentation, it is "digested" and then distributed as food to the plant as a whole. But it is Hales

[54] Hadley, P. B., Johannes Müller, Popular Science Monthly, 1908.
[55] Thomson, J. A., The Science of Life, p. 70.

(1677-1761) to whom the botanist looks as the Harvey of plant physiology, for in his *Vegetable Staticks,* published in 1727, he laid the foundations of the physiology of plants by making "plants speak for themselves through his incisive experiments." For the first time it became clear that green plants derive an important element of their food from the atmosphere, and also that the leaves play an active rôle in the movements of fluids up the stem and in eliminating superfluous water through evaporation.[56]

Still the picture was incomplete, and so it remained until the biologist had recourse to further data from the chemist. In 1779 Priestley, the discoverer of oxygen, showed that this gas under certain conditions is liberated by plants. This fact was seized upon by Ingen-Housz (1730-1799), who demonstrated that carbon dioxide from the air is broken down in the leaf during exposure to sunlight; the plant retaining the carbon and returning oxygen—the process of carbon-getting being quite distinct from that of respiration in which carbon dioxide is eliminated. It remained then for de Saussure to show, by quantitative studies of the plant's income, that, in addition to the fixation of carbon, the elements of water are also employed, while from the soil various salts, including the element nitrogen, are obtained. But it was nearly the middle of the last century before the influence of Liebig (1803-1873) and the crucial experiments of Boussingault (1802-1887) established the part played by the chlorophyll of the green leaf in making certain chemical elements available to animals. The realization of the cosmical function of green plants—the link they supply in the circulation of the elements in nature—is a landmark in biological progress, and we may leave the subject here since, except for details in regard to some of the more evident chemical products of photosynthesis and the influence of ex-

[56] Darwin, F., Stephen Hales, in Makers of British Botany, 1913, p. 65.

ternal factors, the matter still stands essentially where it was in de Saussure's day.[57]

Histology

Studies on the physiology of plants and animals naturally involved the progressive analysis of the physical basis of the phenomena under consideration, but the Aristotelian classification of the materials of the body as unorganized substance, homogeneous parts or tissues, and heterogeneous parts or organs practically represents the level of analysis until the beginning of the last century. It is true, as we have mentioned, that Hooke in 1665 discovered that cork tissue under the microscope seemed to be composed of little boxes or 'cells,' and somewhat similar though more extensive observations were made by the contemporary microscopists. But another century had nearly elapsed before these microscopic elements were looked at from the point of view of their relation to the development of organisms. Wolff (1733-1794) in 1759 attempted to show the falsity of the prevailing idea, that all organisms are preformed in the germ and that the adult state is attained merely by an unfolding and enlarging, by a critical study of the development of animals and plants.[58] And he not only proved his point but also showed that both plants and animals in early developmental stages show a similar fundamental structure, "since every organ is composed at first of a little mass of clear, viscous, nutritive fluid, which possesses no organization, but is at most composed of globules. In this semifluid mass cavities are now developed; these, if they remain round or polygonal, become the subsequent cells; if they elongate, the vessels; and the process is identically the same,

[57] Spoehr, H. A., The Development of Conceptions of Photosynthesis since Ingen-Housz, Scientific Monthly, 9, 1919, p. 32.

[58] Wolff, C. F., Theoria Generationis, 1759; Wheeler, W. M., Wolff and the Theoria Generationis, Woods Hole Biol. Lectures, 1898, pp. 265-284.

whether it is examined in the vegetating point of a plant, or in the young budding organs of an animal." But Wolff's refutation of preformation, chiefly through the opposition of Haller, proved abortive, and his observations on cells were so far ahead of the times that they had but slight influence on biological advance. It was not until the revival of interest in plant anatomy early in the last century that the cell became a particular object of study—and still it was the cell wall rather than the contents on which attention was fixed. Then the English botanist Brown discovered the cell nucleus in 1831,[59] quickly followed by the classic investigations of the botanist Schleiden (1804-1881) and the zoologist Schwann (1810-1882), published in 1838 and 1839,[60] which taken together clearly showed that all organisms are composed of units or cells which are at once structural entities and centers of physiological activities. Each cell carries on a double life; one a quite independent and self-contained life; the other a dependent life in so far as the cell has become an integral part of the organism. The life of the organism is the life of the individual cells which compose it. And further, not only are all organisms congeries of cells, but the egg is a cell and the development of animals and plants consists in the multiplication of this initial cell into the multitude of different kinds which constitute the adult. "The elementary parts of all tissues are formed of cells in an analogous, though very diversified manner, so it may be asserted that there is one universal principle of development for the elementary parts of organisms, however different, and that this principle is the formation of cells."[61]

Unquestionably the launching of the cell theory represents one of the greatest generalizations in biology, and only needed

[59] Farmer, J. B., Robert Brown, in Makers of British Botany, 1913, p. 119.

[60] Schleiden, M. J., Ueber Phytogenesis, 1838; Schwann, T., Mikroscopische Untersuchungen ueber die Uebereinstimmung inder Structur und dem Wachstum der Thiere und Pflanzen, 1839. English trans. by H. Smith, 1847.

[61] Schwann, *op. cit.,* English trans., p. 165.

for its consummation the full realization that the viscid, jelly-like material which zoologists interpreted as the true living matter of animals, and the quite similar material which botanists considered the true living part of plants, are practically identical. This conception was grasped in the early sixties by Schultze (1825-1874) in the formulation of the protoplasm theory, and thenceforth not only morphological elements—cells—but also the material of which they are composed—protoplasm—was recognized as fundamentally the same in all living beings. Indeed, the realization of a common physical basis of life in both plants and animals—a common denominator to which all vital phenomena are reducible—gave content to the term biology and created the science of life in its modern form.[62]

Embryology

The enunciation of the cell theory came, as we have seen, from combined studies on the adult structure and on the development of plants and animals from the germ or egg, and accordingly implies that the science of embryology has a history of its own. As a matter of fact, Aristotle discussed the wonder of the beating heart in the hen's egg after three days' incubation, but there the subject practically rested until Fabricius (1537-1619), early in the seventeenth century, published a treatise which illustrated the obvious sequence of events in the hen's egg up to the time of hatching.[63] This beginning was built upon by a pupil of Fabricius, the celebrated Harvey, who added many details of interest and insisted, as Aristotle had before him, that the embryo arises as a gradual differentiation of unformed material of the egg.[64]

However, little progress in embryology was possible without the microscope, which was first applied to the problem by

[62] Wilson, E. B., The Cell in Development and Inheritance, 2d ed., 1900; Verworn, *op. cit.*

[63] Fabricius, Opera Omnia, edited by Bohn, 1687; Russell, *op. cit.*, p. 113.

[64] Harvey, Exercitationes de Generatione Animalium, 1651.

the versatile Malpighi in two treatises sent to the Royal Society in 1672.[65] It is but necessary to study his splendid series of illustrations to realize how animal development was placed upon a plane so advanced that for over a century it was unappreciated. One conclusion of Malpighi, however, was seized upon by contemporary biologists. Apparently, unbeknown to him, some of the eggs which he studied were slightly incubated so that he thought traces of the future organism are preformed in the egg. This error, coupled, for example, with Swammerdam's observation of the fact that parts of the adult insect are delineated in the larva ready to pupate, crystallized the preformation theory which denied all true development, or epigenesis, as advocated by Aristotle and Harvey, and held that the future adult characters pre-exist in miniature in the egg. Even the acute observations of Wolff in his embryological classic, to which we have referred, failed of fruition since it negated the preformation idea which in the years that had elapsed since Malpighi had become the dominant question in embryology. Indeed, the theory was carried to a *reductio ad absurdum* by Haller, Bonnet (1720-1793), and others who accepted the logical conclusion that:

> Each seed includes a plant: that plant, again,
> Has other seeds, which other plants contain:
> Those other plants have all their seeds; and those,
> More plants, again, successively inclose.
>
> . . . .
>
> So Adam's loins contain'd his large posterity,
> All people that have been, and all that e'er shall be.
>
> Amazing thought! What mortal can conceive
> Such wond'rous smallness! Yet we must believe
> What reason tells: for reason's piercing eye
> Discerns those truths our senses can't descry.

[65] Malpighi, De Formatione Pulli in Ovo and De Ovo Incubato.

So Baker expressed it in one of the few departures from prose permitted in the Philosophical Transactions of the Royal Society.[66]

The truth of the matter is that the time was not ripe for theories of development. The preformationists were wrong, but so were Aristotle, Harvey, and Wolff, who went to the other extreme and denied all egg organization and therefore tried to get something out of nothing. It remained for the present generation of embryologists to work out many of the details of the origin of the germ cells and their organization, and to reach a level of analysis deep enough to suggest how "the whole future organism is potentially and materially implicit in the fertilized egg cell," and thus that "the preformationist doctrine had a well concealed kernel of truth within its thick husk of error."[67]

The real step to progress, Baker's implicit confidence in "reason" to the contrary, came in the accurate and comprehensive studies of von Baer (1792-1876) published in the thirties of the last century.[68] Taking his material from all the chief groups of higher animals von Baer founded comparative embryology. Among his achievements may be mentioned the clear discrimination of the chief developmental stages, as cleavage of the egg, germ layer formation, tissue and organ differentiation; the importance of the facts of development for classification; and the discovery of the egg of mammals. His observations on the origin and development of the germ layers, which afforded the key to many general problems of morphogenesis, and his emphasis on the resemblance between

[66] Baker, H., The Microscope Made Easy, 1742; Woodruff, L. L., Baker on the Microscope and the Polype, Scientific Monthly, 1918.

[67] Thomson, *op. cit.;* Whitman, C. O., Woods Hole Biological Lectures, 1894, pp. 205-272; Wilson, E. B., The Problem of Development, Science, 21, 1905; Woodruff, L. L., The Foundations of Biology, 1922, pp. 251-260.

[68] Von Baer, Ueber Entwickelungsgeschichte der Thiere; Beobachtung und Reflexion, 1828-1837. *Cf.* Huxley, Philosophical Zoology Selected from the Works of K. E. von Baer, in Scientific Memoirs, February and May, 1853.

certain embryonic stages of higher animals and the adult stages of lower forms, were exaggerated and crystallized by his successors, under the influence of the evolution theory, as the germ layer theory and the recapitulation theory, or von Baer's law. Both were of the greatest importance in stimulating research for half a century—and if the present generation has not inherited its forebears' implicit faith in the theories, it at least has profited immensely by the facts they accumulated.[69]

From every point of view von Baer created an epoch in embryology synchronous with the formulation of the cell theory by Schleiden and Schwann, and it thenceforth became the problem of the embryologist to interpret development in terms of the cell. Space will not permit us to follow the establishment of the fact that the egg and the sperm are really single, nucleated cells; that fertilization consists in the fusion of egg and sperm and the orderly arrangement of their chief nuclear contents, or chromosomes; that the new generation is the fertilized egg, since every cell of its body as well as every chromosome in every cell is a lineal descendant by division from the egg, and so from the germ cells which united at fertilization to form it. Such, however, are the chief results of cytological study since von Baer; but embryologists have not been content to employ merely the descriptive method, and the dominant note of the most modern research, first emphasized by Roux, is physiological—the experimental study of the significance of fertilization, the dynamics of cell division, the basis of differentiation, the effect of environmental stimuli, and so on.[70]

Genetics

It is but natural that the study of inheritance could be little more than a groping in the dark until embryology, under the

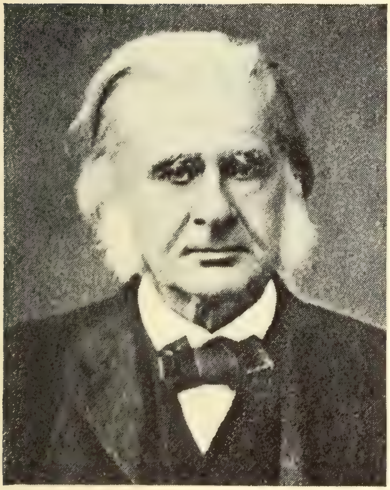
[69] Locy, *op. cit.*, pp. 214-222.
[70] Wilson, *op. cit.*

influence of the cell theory, afforded a body of facts which clearly indicated that the fertilized egg is typically the sole bridge of continuity between successive generations. Indeed, the present science of genetics has a history confined solely to post-Darwinian times and mostly to this century.

Although clearly suggested by a number of workers, the conception of the continuity of the germ cells—or germ plasm—was first forced upon the attention of biologists and given greater precision by Weismann (1834-1914) in a series of essays culminating in 1892 in his volume entitled *The Germ Plasm*. He identified the chromatin material which constitutes the chromosomes of the cell nucleus as the specific bearer of hereditary characters, and emphasized a sharp distinction between the cellular derivatives of the fertilized egg—on the one hand, the somatic cells which by division and differentiations build up the body of a higher plant or animal; and on the other, the germ cells which are destined to play but little part in the life of the individual which bears them, but instead are to be liberated and give rise to the next generation. The importance of this distinction can hardly be overemphasized, for at once it makes clear that, for all practical purposes, the bodily characteristics of an individual are negligible from the standpoint of heredity, since the offspring are descendants not from the body cells, but from the germ cells and these in turn from the germ cells of the preceding generation. As Weismann insisted, this view makes it difficult to conceive how modifications of the soma can so specifically affect the germ cells which it bears that the latter can reproduce the modifications—in other words that so-called 'acquired characters' cannot be inherited. And there is no satisfactory evidence that such characters are inherited. The practical bearings of this conclusion are obviously of the highest importance, lying as they do at the very root of many questions in regard to the factors of evolu-

Karl Ernst von Baer.

Theodor Schwann.



Thomas Henry Huxley.

Gregor Johann Mendel.

tion, not to mention such practical ones as education and eugenics.

While this viewpoint has been gradually gaining content and precision, the science of heredity has been advancing not only by exact studies of the structure and physiology of the germ cells, but also by statistical investigations of the results of heredity—the various characters of animals and plants in parent and offspring.

The first studies of this type which attracted the attention of biologists were made by Galton (1822-1911), who in the eighties and nineties of the last century amassed a large amount of data in regard, for example, to the stature of children with reference to that of their parents, and formulated his well-known 'laws' of inheritance.[71] But the epoch-making work which eventually created the science of genetics was that of an Austrian monk, Gregor Mendel (1822-1884), who combined in a masterly manner the experimental breeding of pedigree strains of plants and the statistical treatment of the data thus secured in regard to the inheritance of sharply contrasting characters, such as the flower color in sweet peas. Mendel's work was published in 1865 in an obscure natural history periodical[72] and he himself abandoned his teaching and research to become the abbot of his monastery. Thus terminated prematurely the scientific work of one of the epoch makers of biology, and the now famous 'Mendelian laws' of inheritance were unknown to science until 1900 when other biologists, coming to similar results, unearthed his forty-year-old paper. We can pause only to say that the fundamental principle of the segregation of the genes of the 'alternative' characters within the germ cells, which Mendel's work indicated, has been extended to other plants and to animals, and from being, as at

[71] Galton, F., Natural Inheritance, 1889.

[72] Mendel, J. G., Versuche über Pflanzen-Hybriden, Verhandlungen des naturforschenden Vereines in Brünn, 4, 1865.

first thought, a principle of rather limited application, now seems to be the key to all inheritance. And the present results are extremely convincing because cytological studies on the architecture of the chromosome-complex of the germ cells keep pace and afford a picture of the physical basis—of the mechanism by which the segregation and distribution of genes by the Mendelian formula takes place.[73] Such is the deeply hidden germ of truth in the old preformation theories!

Origin of Life

With our present conception of the complexities of organisms it is difficult to realize that up to the seventeenth century naturalist and layman saw nothing more incongruous in the spontaneous origin of nearly all kinds of plants and animals, than does the boy of today who believes that horse hairs soaked in water are transformed into worms. Even Aristotle thought that certain of the vertebrates, such as eels, arose spontaneously, and Harvey accepted the same view of the origin of many forms of life. It remained for Redi (1626-1698) to lay aside discussion for experiment. By protecting decaying meat from contamination by flies he demonstrated that these insects are not developed from the flesh and that the apparent transformation of meat into maggots is due solely to the eggs of flies being deposited thereon.[74] But the time-honored doctrine was not overthrown by this experiment or the long series which Redi made, for the presence of parasites within certain recondite parts of higher animals baffled Redi himself, while improvements in the microscope soon revealed a microcosm whose origin seemed plausibly explained as spontaneous. Biogenesis, or all life from pre-existing life, was placed on a secure foundation only within the past sixty years

[73] Morgan, T. H., The Physical Basis of Heredity, 1919.

[74] Redi, F., Esperienze Intorno alla Generazione Degl'Insetti, 1668. English trans., 1909.

by the working out of the remarkably complex life histories of internal parasites, and by the classical demonstrations of Pasteur (1822-1895), Koch (1843-1910), and others that micro-organisms are not the result but the cause of decay and disease; a fact which is at the basis of, and is attested by the methods now universally in use in food preservation and aseptic surgery—to mention but two instances.[75] The vicissitudes of the doctrine of biogenesis—"la génération spontanée est une chimère," wrote Pasteur—are an eloquent illustration of the aphorism of the old London microscopist that "the likeliest method of discovering truth is by the observations and experiments of many upon the same subject."[76]

Organic Evolution

Since we have every reason to believe that all life now arises from pre-existing life and has done so since matter first assumed the living state, it apparently follows that the stream of life is continuous from the remote geological past to the present and that all organisms of today have an ancient pedigree. This leads up to a question which has interested and perplexed thinking men of all times: how things came to be as they are today. It was the Greek natural philosophers who projected the idea of history into science and attempted to substitute a naturalistic explanation of the earth and its inhabitants for the established theogenies, and thus started the uniformitarian trend of thought which culminated in the establishment of organic evolution during the past century.

Again it is Aristotle who is singled out among the Greeks for his combination of sound philosophy and induction which reaches no higher expression than in his statements regarding the relationships of organisms. He says, in substance: Al-

[75] Huxley, T. H., Biogenesis and Abiogenesis, Presidential address, British Assn. Adv. Sci., 1870, Collected Essays, vol. 8; Woodruff, L. L., The Origin of Life, in The Evolution of the Earth and Its Inhabitants, 1918.

[76] Baker, *op. cit.*, p. v.

though the line of demarcation is broadly defined, yet nature passes by ascending steps from one to the other. The first step is that of plants; which, compared with animals, seem inanimate. The second step nature takes is from plants to plant-animals, the zoophytes. The third step is the development of animals, which arise from an increased activity of the vital principle, resulting in sensibility; and with sensibility, desire; and with desire, locomotion. Man is the head of animal creation. To him belongs the God-like nature. He is pre-eminent by thought and volition. But although all are dwarf-like and incomplete in comparison with man, he is only the highest point of one continuous ascent.[77]

Broadly speaking, Aristotle apparently held substantially the modern idea of the evolution of life from a primordial mass of living matter to the highest forms, and believed that evolution is still going on—the highest has not yet been attained. In looking for the effective cause of evolution Aristotle rejected Empedocles' hypothesis of the chance play of forces, which embodied in crude form the idea of the survival of the fittest, and substituted secondary natural laws to account for the fact that "Nature produces those things which, being continually moved by a certain principle contained in themselves, arrive at a certain end." Aristotle's rejection of the hypothesis of the survival of the fittest to account for adaptations of organisms was a sound induction from his necessarily limited knowledge of nature—but had he accepted it he would have been "the literal prophet of Darwinism."[78]

Although the thread of continuity of evolutionary thought is not broken from Aristotle to the present, no historical interest will be served in following the poetical expression by Lucretius, the discussion at once broad and narrow of the most liberal medieval churchmen, the "Arab philosophy—a

[77] Lewes, *op. cit.*, pp. 189-196; Osborn, *op. cit.*, p. 48.
[78] Osborn, *op. cit.*, pp. 55-57.

system of Greek thought expressed in a Semitic tongue and modified by Oriental influences," or the vagaries of the Renaissance naturalists and speculative evolutionists, who, with a minimum of fact and a plethora of imagination were the worst enemies of the evolution idea. In truth, the great natural philosophers from Bacon and Leibnitz to Kant and Hegel laid the broad foundation for our modern attack on evolution, but from the strictly biological viewpoint, two Frenchmen, Buffon and Lamarck, and two Englishmen, Erasmus Darwin and his grandson, Charles Darwin, stand pre-eminent—and the greatest is Charles Darwin.

Buffon (1707-1788) was a peculiarly happy combination of popular writer and scientist—entertaining by each new volume of his great *Histoire Naturelle* the social set of Paris, and instructing them at the same time. And it was largely between the lines of his Natural History that Buffon's evolutionary ideas found expression: but expressed they were, though sometimes difficult to decipher—beyond the ken, Buffon hoped, of the censor and dilettante, for apparently he was not of martyr stuff.[79] It is not strange, therefore, that there are some differences of opinion amongst biologists today as to just how much weight is to be placed on some of Buffon's statements, but certainly it is not exaggerating to ascribe to him not only the recognition of the factors of geographical isolation, struggle for existence, artificial and natural selection in the origin of species, but also, which is equally important, the propounding of a theory of the origin of variations. He thought that the direct action of the environment brings about modifications of the structure of animals and plants and these are transmitted to the offspring.

When Buffon's influence was at its zenith, Erasmus Darwin (1731-1802), a successful medical practitioner, expressed con-

[79] Butler, S., Evolution Old and New, 3d ed., 1911, p. 78; Lovejoy, A. O., Buffon and the Problem of Species, Popular Science Monthly, 1911.

sistent views on the evolution of organisms in several volumes of prose and poetry.[80] Although a contemporary critic in the *Edinburgh Review* remarked that Darwin's "reveries in science have probably no other chance of being saved from oblivion, but by having been married to immortal verse," today biologists recognize him as the anticipator of Lamarck's doctrine that variations spring from within the organism through its reaction to environmental conditions. "All animals undergo perpetual transformations which are in part produced by their own exertions in consequence of their desires and aversions, of their pleasures and their pains, or of irritations, or of associations; and many of these acquired forms or propensities are transmitted to their posterity."[81] "Thus it would appear that all nature exists in a state of perpetual improvement by laws impressed on the atoms of matter by the great Cause of Causes; and that the world may still be in its infancy, and continue to improve forever and ever."[82]

While Cuvier was extending and synthesizing the knowledge of anatomy of living and extinct forms and founding the so-called school of facts, his fellow countryman, Lamarck (1744-1829), on the basis of work first on plants and then on animals, carried on in a fearless manner the evolutionary inspiration of Buffon and Erasmus Darwin (though the latter's works may not have been known to him), and established the coterie of evolutionists in Paris each of whose essays Cuvier hailed as a "new folly." Lamarck developed with great care the first complete and logical theory of organic evolution, and is the one outstanding figure in biological uniformitarian thought between Aristotle and Charles Darwin. "For nature," he

[80] Botanic Garden, 1791, Zoonomia, 1794-1796; Phytologia, 1800; Temple of Nature, 1802. It is said that Paley's famous Natural Theology was written to counteract the influence of the Zoonomia.

[81] Zoonomia, 1st ed., 1, p. 503. *Cf.* E. Krause, Life of Erasmus Darwin, with a Preliminary Notice by Charles Darwin, 1879.

[82] Zoonomia, 3d ed.

writes, "time is nothing. It is never a difficulty, she always has it at her disposal; and it is for her the means by which she has accomplished the greatest as well as the least of her results. For all the evolution of the earth and of living beings, nature needs but three elements—space, time, and matter."[83]

In regard to the factors of evolution, Lamarck emphasized the indirect action of the environment in the case of animals, and the direct action in the case of plants. The former are induced to react and thus adapt themselves, while the latter, without a nervous system, are molded directly by their surroundings. And, so Lamarck believed, such bodily modifications—acquired characters—are transmitted to the next generation and bring about the evolution of organisms.[84]

Through the influence of Cuvier, and the relative weakness of Lamarck's successors—the foremost was Étienne Geoffroy Saint-Hilaire (1772-1844)[85]—the French School of evolutionists dwindled to practical extinction, while in Germany, Goethe (1749-1832), the greatest poet of evolution, and Treviranus (1776-1837) "brilliantly carried the argument without carrying conviction," for the man and the moment must agree. Then in England the uniformitarian ideas of Hutton (1726-1797), elaborated by Lyell (1797-1875) in his "Principles of Geology, being an attempt to explain the former changes of the earth's surface by reference to causes now in action" (1830-1833), created an epoch in geology. The prevailing doctrine of cataclysms, emphasized among biologists, especially by Cuvier, gradually gave place to that of uniformity—an orderly evolution of the earth—and paved the way for the next logical step—the evolution of the earth's inhabitants.[86]

[83] Hydrogéologie, 1802.

[84] Philosophie Zoologique, 1809. English trans. by H. Elliot, 1914; Osborn, *op. cit.*, pp. 165-167; Packard, A. S., Lamarck, the Founder of Evolution, 1901.

[85] Philosophie Anatomique, 1818.

[86] Judd, J. W., The Coming of Evolution, 1910.

It has been said, and truly, that the idea of development saturated the intellectual atmosphere. But intrenched prejudices which hampered the acceptance of evolution in the inorganic world were immeasurably augmented when the world of life was approached, and only an overwhelming amount of scientific evidence, impartially and convincingly presented, could carry conviction, so completely had the dogma of special creation become established since the middle of the sixteenth century.[87] This, in part, accounts for the slight influence of the work of the earlier evolutionists, as well as for the reception accorded the evolutionary views expressed anonymously in the *Vestiges of the Natural History of Creation*[88] by Chambers (1802-1871). The ten editions of this work (1844-1860) created a furor, especially in England, and were opposed alike by biologist and layman.

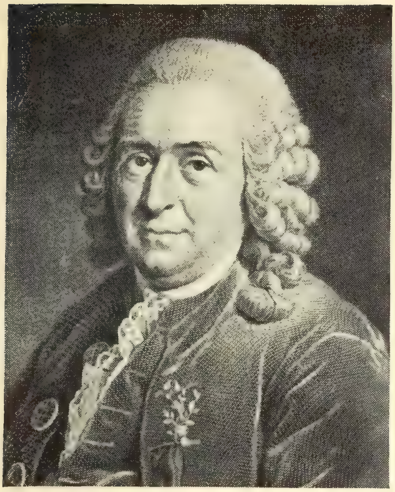
The case for evolution at the time, as it appeared to the erudite Whewell, is thus summarized in the first edition (1838) of his well-known *History of the Inductive Sciences* and reiterated in the third edition (1857): "Not only is the doctrine of the transmutation of species in itself disproved by the best physiological reasonings, but the additional assumptions which are requisite, to enable its advocates to apply it to the explanation of the geological and other phenomena of the earth, are altogether gratuitous and fantastical. Such is the judgment to which we are led by the examination of the discussions which have taken place on the subject."[89]

And then appeared the greatest work of Charles Darwin (1809-1882)—the result of twenty years' labor. The *Origin of Species* (1859) presented a huge amount of data which most reasonably could be explained by assuming the origin of

[87] Lovejoy, A. O., The Argument for Organic Evolution before "The Origin of Species," Popular Science Monthly, 1909.

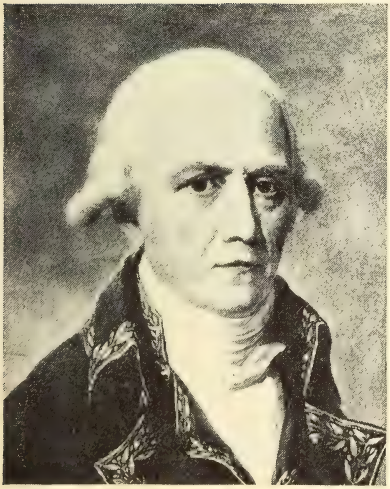
[88] Ireland, A., Introduction to the 12th edition of the Vestiges, 1884.

[89] 3d ed., 3, p. 481.

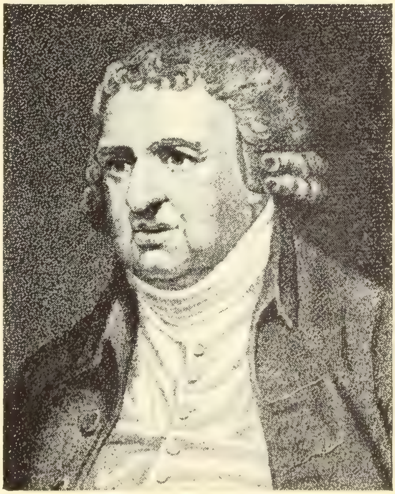


Carolus Linnæus.

Comte de Buffon.



Jean Baptiste de Lamarck.



Erasmus Darwin.

existing species by descent with modifications from others, and also offered as the explanation of their origin the theory of "natural selection, or the preservation of favored races in the struggle for life." In Darwin's words: "As many more individuals of each species are born than can possibly survive, and as, consequently, there is frequently recurring struggle for existence, it follows that any being, if it vary however slightly in any manner profitable to itself, under the complex and sometimes varying conditions of life, will have a better chance of surviving, and thus be naturally selected. From the strong principle of inheritance any selected variety will tend to propagate its new and modified form."

Facts and theories had been brought forward before in support of evolution—indeed, the theory of natural selection had been suggested before Darwin's time and again independently by Wallace (1822-1913) just as Darwin was completing his long studies preparatory to publication.[90] But the stupendous task of thinking evolution through for the endless realm of living nature remained to be done, and Darwin did it convincingly by his brilliant, scholarly, open-minded, and cautious marshaling and interpreting of data.[91]

It was the combination of the facts and the theory to account for the facts which won the thinking world to organic evolution and "made the old idea current intellectual coin." Darwin supplied the Ariadne thread which led from the maze of transcendental affinity to genetic continuity. Now we know that evolution is a bird's-eye view of the results of heredity since the origin of life and that the facts of inheritance hold the key to the factors of evolution.

[90] Wallace, A. R., The Origin of the Theory of Natural Selection. Reply on receiving the Darwin-Wallace medal of the Linnæan Society, July, 1908, Popular Science Monthly, April, 1909, p. 396; Hooker, J., The First Presentation of the Theory of Natural Selection, *op. cit.*, p. 402.

[91] *Cf.* the Darwin Centennial Number of the Popular Science Monthly, April, 1909.

Darwin spent the twenty years subsequent to the publication of the *Origin of Species,* as he had spent the preceding twenty years, in study and research, the results of which appeared in nine additional volumes. Three of these perhaps may be singled out as primarily an elaboration of the *Origin: The Variation of Animals and Plants under Domestication* (1868), *The Descent of Man* (1871), and *The Expression of the Emotions* (1872). Singly and collectively these volumes are a monument to genius and labor. Erasmus Darwin was wont to say that the world is not governed by brilliancy but by energy. His grandson revolutionized biological thought through their combination.

Among Darwin's early converts from the ranks of professional biologists must be mentioned Huxley (1825-1895) and Hooker (1817-1911) in England, Haeckel (1834-1919) and Weismann in Germany, and Gray (1810-1888) in America—men with the courage of their convictions when courage was necessary, whose support did so much for the promulgation of evolutionary ideas.

> Thoughts that great hearts once broke for, we
> Breathe cheaply in the common air.

Today no representative biologist questions the fact of evolution—"evolution knows only one heresy, the denial of continuity"—though in regard to the factors there is much difference of opinion. It may well be that we shall have reason to depart widely from Darwin's interpretation of the effective principles at work in the origin of species, but withal this will have little influence on his position in the history of biology. The great value which he placed upon facts was exceeded only by his demonstration that this "value is due to their power of guiding the mind to a further discovery of principles." Darwin brought biology into line with the other inductive sci-

ences, recast practically all of its problems, and instituted new ones.

Such, in briefest form, is a survey of the epochs and epoch makers in biological progress—a mere glance of the biologist into the past "to the mountains whence cometh his strength." Building upon these foundations the biological sciences are developing with amazing rapidity at the present time chiefly through the cumulative influence of an all-pervading desire of students of life phenomena to observe nature at work—actually to control and modify biological processes. Today the investigator insists upon interrogating nature experimentally and observing the *modus operandi.* In a word, the modern biological ideal is to construct an account of the living organism which can be verified by actual observation provided the proper conditions are afforded. Biology has emerged from the phase of development in which the descriptive note was dominant and has become in fact an experimental science.

APPENDIX I

BIOGRAPHIES

Brief data in regard to the more important scientists mentioned in the text. The titles of books referred to only by author's name will be found in the Bibliography, Appendix II.

ABEL, NIELS HENRIK (1802-1829). Norwegian mathematician. Studied at Christiania; visited Germany and France; at Freiburg made brilliant researches in elliptic, hyperelliptic, and a new class known as "Abelian functions." His works originally appeared in Crelle's Journal; later edited by Holmboë, in 1839. *Cf.* C. A. Bjerknes, Niels Henrik Abel: Tableau de sa vie et son action scientifique, Paris, 1885.

ADAMS, JOHN COUCH (1819-1892). British astronomer. Shared with Leverrier the discovery of Neptune by its effect on Uranus.

AGASSIZ, JEAN LOUIS RODOLPHE (1807-1873). Swiss zoologist and geologist. Studied at Zurich, Heidelberg, and Munich. Appointed professor at the Academy of Neuchâtel, 1832. Professor of zoology and geology, Harvard University, 1847. Founded at Cambridge the Museum of Comparative Zoology, 1859. Études sur les glaciers, 1840; Poissons fossiles, 1833-1844; Essay on Classification, 1857. E. C. Agassiz, Life, 1885; Jordan; Russell.

D'ALEMBERT, JEAN LE ROND (1717-1783). French mathematician and physicist. His chief contributions were in integral calculus, mechanics, mathematical astronomy, and the history and philosophy of science. His name is given to that law of dynamics known as "d'Alembert's principle." Traité de dynamique, 1743. *Cf.* Condorcet's Éloge, read before the Academy, 1784.

ALKARISMI (ninth century A. D.). Arabian mathematician. Wrote an algebra based on the work of Brahmagupta which served as a founda-

tion for many later treatises. The book discusses five types of quadratic equations, and deals with the simplest matters most needed in problems of distribution, inheritance, partnership, land-measurements, etc.

AMPÈRE, ANDRÉ MARIE (1775-1836). French physicist. Professor at Lyons, Bourg, Paris, and École Polytechnique. Chief work was the development of the relations between electricity and magnetism; electrodynamics. His celebrated papers on this theory appeared from 1820-1828. *Cf.* his Journal et correspondance, published at Paris, 1872.

ANDREWS, THOMAS (1813-1885). Irish physico-chemist. Pioneer in work on compressed gases leading to the liquefaction of the "permanent" gases.

APOLLONIUS (260-200 B. C.). Greek mathematician. Called "the great Geometer." The last of the famous Alexandrian group of mathematicians. His important work was on conic sections.

ARCHIMEDES (287-212 B. C.). Greek scientist. Devoted life to the study of mathematics. Studied at Alexandria, and had close association with Conon of Samos. Chief results were in geometry, mechanics, and hydrostatics. *Cf.* T. L. Heath's The Works of Archimedes, 1897.

ARDUINO, GIOVANNI (1713-1795). Professor of mineralogy at Padua. He exerted a strong influence upon his colleagues and the many foreign geologists who came to Italy for study. List of writings printed in Bibliographie géologique et paleontologique de l'Italie, Bologna, 1881. *Cf.* Zittel.

ARGELANDER, FRIEDRICH WILHELM AUGUST (1799-1875). Compiled the Northern Durchmusterung of faint stars; initiated the Gesellschaft Catalog.

ARISTARCHUS OF SAMOS (c. 260 B. C.). Concluded that the sun and not the earth is the center of our system; made first estimate of the distance of the sun.

ARISTOTLE (384-322 B. C.). Greek philosopher, student of Plato. The founder of natural history as a science; his work and methods were not surpassed for nearly twenty centuries. Promoted geometry by improving some of the most difficult definitions. His Physics hinted at the principle of virtual velocities; he defined continuity. Aristotelis Opera, Berlin, 1831-1870; History of Animals, English translations by R. Creswell, 1862, and D. W. Thompson, 1910; On the Parts of Ani-

mals, translated by W. Ogle, 1882; On the Generation of Animals, German translation by Aubert and Wimmer, 1860.

Arrhenius, Svante August (1859—). Swedish chemist. Associated especially with the conception and development of the theory of ionization.

Avogadro, Amadeo (1776-1856). Italian physicist, notable for his hypothesis, enunciated in 1811, which led ultimately to a consistent conception of molecular weight.

Bacon, Francis, Sir (1561-1626). British philosopher and statesman. Studied at Cambridge; took a prominent part in the public life of the Elizabethan period. Failed to found science anew, but succeeded in giving the study a new spirit. Novum Organum. *Cf.* J. Spedding's Life and Letters, 1861; and Life and Times of Francis Bacon, 1878.

Bacon, Roger (1214-1294). British philosopher and scientist. Studied at Oxford and Paris; entered Franciscan Order in 1250; taught philosophy at Oxford. Sought to restore experimental science. Opus Majus. *Cf.* E. Charles' Roger Bacon, sa vie, ses ouvrages, ses doctrines, d'apres des textes inédites, 1861.

Baer, Karl Ernst von (1792-1876). Russian embryologist. Studied at Würzburg. Professor at Dorpat, Königsberg, and St. Petersburg. Founder of Comparative Embryology. Ueber Entwickelungsgeschichte der Tiere, etc., 1828-1837; Leben und Schriften, 1864. *Cf.* Locy, and Russell.

Beaumont, Léonce Élie de (1798-1874). French geologist. Member of a noble family of Normandy. Professor of geology in School of Mines, 1827. General Inspector of Mines, 1835. Prepared a geological map of France which exerted a powerful influence on whole development of geology in France. *Cf.* Zittel.

Belon, Pierre (1517-1564). French zoologist and traveler. Life was marred by many vicissitudes. De aquatilibus libri duo cum iconibus ad vivam eorum effigiem, 1553; L'histoire de la nature des Oyseaux avec leur descriptions et naifs portraicts retirez du naturel, 1555. *Cf.* Miall's Early Naturalists.

Bernard, Claude (1813-1878), French physiologist. Notable studies on the pancreas, on glycogen, and on vaso-motor nerves. Leçons

sur les phénomènes de la vie communs aux animaux et aux végétaux. *Cf.* L'Œuvre de Claude Bernard, 1881; Foster's Life of Bernard, 1899.

Bernoulli. A family with three generations of famous mathematicians. Jacques (1654-1705), Jean (1667-1748), Nicolaus (1687-1759), Nicolaus (1695-1726), Daniel (1700-1782), Jean (1710-1790), Jean (1744-1807), Jacques (1759-1789).

Bernoulli, Jacques (1654-1705). Swiss mathematician. Professor of mathematics at Basel. The first to solve Leibnitz's problem of the isochronous curve (1690), and proposed the famous problem of isoperimetrical figures (1696). Ars Conjectandi, 1713, contained the celebrated "Bernoulli's theorem" in the theory of probability.

Bernoulli, Jean (1667-1748). Swiss mathematician. Professor of mathematics at Gröningen and succeeded his brother at Basel. He discovered exponential calculus, and the curve linea brachistochrona.

Berthelot, Marcellin Pierre Eugène (1827-1907). French chemist, known particularly for his investigations of the heat changes associated with chemical changes.

Berzelius, Jöns Jakob (1779-1848). Swedish chemist. Outstanding figure in the development of quantitative analytical methods. Lehrbuch der Chemie.

Bessel, Friedrich Wilhelm (1784-1846). German astronomer. Director of the observatory at Königsberg. Published Bradley's Greenwich Observations; improved methods of reduction of observations; first measured the distance of a fixed star.

Bhaskara (1150 A. D.). Hindu mathematician. Introduced algebraic symbolism, and made considerable progress in abbreviated notation. Siddhānta S'iromani.

Bischof, Karl Gustav (1792-1870). Professor of chemistry at Bonn. Text-book of chemical and physical geology, 1846-47. *Cf.* Zittel.

Black, Joseph (1728-1799). British chemist and physicist. Studied medicine at Glasgow, and chemistry under William Cullen. Chief contributions were in the chemistry of alkaline substances and in the development of the doctrine of latent heat. Did not publish his studies, but announced them in lectures at Glasgow and Edinburgh, where he taught Chemistry, Anatomy, and Medicine. Dissertatio de humore acido

a cibo orto, 1754. *Cf.* John Robinson's Lectures on the Elements of Chemistry, 1803; and Foster.

BOLTZMANN, LUDWIG (1844-1906). Austrian physicist. Studied at Vienna, Heidelberg, and Berlin. Was professor at Gratz, Munich, Leipzig, and Vienna. Chief work was in mechanics, thermodynamics, and the kinetic theory of gases. Vorlesungen über kinetische Gastheorie, 1896-1898; Vorlesungen über die Prinzipe der Mechanik, 1897-1904.

BOLYAI, JOHANN (1802-1860). Hungarian mathematician. Educated for the army, but distinguished himself by his treatise on non-Euclidean geometry. *Cf.* J. Bolyai's The Science Absolute of Space, translated by Halstead, 1891.

BONNET, CHARLES (1720-1793). Wealthy French lawyer who devoted his life to biological experiment and philosophy. Traité d'Insectologie, 1745. *Cf.* Miall's Early Naturalists.

BORELLI, GIOVANNI ALPHONSO (1608-1679). Italian mathematician and physiologist. Professor of mathematics at Messina, and Pisa. His colleague, Malpighi, turned his attention to physiological problems. De Motu Animalium, 1680-1681. *Cf.* Foster.

BOYLE, ROBERT (1627-1691). English natural philosopher; one of the founders of the Royal Society of London (the first scientific society). Discoverer of Boyle's Law, relating the pressure and volume of a gas. New Experiments Physico-Chemical, 1660; The Sceptical Chymist, 1661.

BRADLEY, JAMES (1692-1762). Successor to Halley as Astronomer Royal of England. Discovered nutation and aberration; constructed by far the most accurate and extensive star catalog up to his time. *Cf.* Biography by Rigaud, 1832.

BRAGG, WILLIAM HENRY, SIR (1862—). British physicist. Studied at King William's College (Isle of Man) and at Trinity College, Cambridge. Professor of mathematics and physics at Adelaide University and Leeds University, and professor of physics at the University of London. Worked, with his son (William L. Bragg), on the structure of crystals. X-rays and Crystal Structure, 1918. Received, with his son, the Nobel prize in 1915, and the Barnard medal in 1914.

BRAMAGUPTA (598). Hindu mathematician. Wrote his Brahmasphuta-siddhānta, called "The Revised System of Brahma."

BRONGNIART, ALEXANDRE (1770-1847). Associate of Cuvier. Suc-

ceeded Haüy as professor of mineralogy at the Museum of Natural History. Traité élémentaire de minéralogie, avec des applications aux arts, 2 vols., Paris, 1807; Histoire naturelle des crustacés fossiles, Paris, 1822; Classification et caractères minéralogiques des roches homogènes et hétérogènes, Paris, 1827. Coadjutor of Cuvier in Essai sur la géographie minéralogique des environs de Paris, 1811. *Cf.* Geikie, Founders of Geology, 1905.

Brown, Robert (1773-1858). Military surgeon. Naturalist to H. M. S. Investigator; Librarian, and President of the Linnean Society. Described 'Brownian movement'; made important studies on the nucleus of plant cells. Prodromus florae Novae Hollandiae, 1810. *Cf.* J. B. Farmer's Essay, in Oliver.

Brücke, Ernst Wilhelm von (1819-1892). Professor of physiology at Vienna. A versatile physiologist. *Cf.* Garrison.

Brunner, Jean Conrad von (1653-1727). Professor of medicine at Heidelberg. Experimenta nova circa pancreas, 1682; Dissertatio de glandulis duodeni, 1687. *Cf.* Foster.

Buckland, William (1784-1856). Professor of mineralogy at Oxford, 1813; first professor of geology at Oxford, 1819. Dean of Westminster, 1845. Reliquiæ diluvianæ, 1824. *Cf.* Life and Correspondence of William Buckland by his daughter, Mrs. Gordon, 1894.

Buffon, George Louis Leclerc, comte de (1707-1788). French naturalist. Head of the Jardin du Roi, Paris. Theorie de la Terre, 1749. Histoire Naturelle, 1750-1804 (several translations). *Cf.* Butler, and Osborn.

Bunsen, Robert Wilhelm von (1811-1899). German chemist, famed particularly as a teacher at Heidelberg; developed many analytical methods, amongst them that of spectroscopic analysis (with Kirchhoff); inventor of the Bunsen burner.

Camper, Peter (1722-1789). Dutch anatomist. Studied at Leyden; professor at Gröningen. Compared fish brain and human brain. Kleinere schriften, 1782. *Cf.* Locy.

Cannizzaro, Stanislao (1826-1910). Italian chemist, who rendered great service to the philosophy of chemistry in 1858 by interpreting the implications of Avogadro's hypothesis.

Cardan, Girolamo (1501-1576). Italian mathematician, physician,

and astrologer. Studied at Pavia and Padua. Professor of medicine at Pavia and Bologna. His important advances paved the way for discoveries which have obscured his own. De subtilitate Rerum, 1551; De varietate Rerum, 1557. *Cf.* Henry Morley, Jerome Cardan, 1854.

Carnot, Sadi Nicolas Léonard (1796-1832). French engineer and physicist. Studied at the École Polytechnique and became a military engineer. Left the army to devote himself to science. Introduced the study of thermodynamics by the publication of his famous Réflexions sur la puissance motrice du feu et sur les machines propres à développer cette puissance, 1824.

Cassini, Giovanni (1625-1712). French astronomer; first director and founder of the Paris observatory.

Cauchy, Augustin Louis (1789-1857). French mathematician. Professor at the École Polytechnique, and at Turin. Researches covered almost the whole realm of mathematics, pure and applied. *Cf.* Œuvres complètes d'Augustin Cauchy.

Cavendish, Henry (1731-1810). English chemist and physicist, best known for his researches on gases, which he was the first to study quantitatively, and for his experiments to determine the density of the earth.

Cayley, Arthur (1821-1895). English mathematician. Professor of pure mathematics at Cambridge. Discovered a new branch of analysis by his theory of invariants. Collected Works published by Cambridge University Press, 1894.

Cesalpino, Andrea (1519-1603). Professor of medicine and botany at Pisa; ardent theologian. Offered a theory of circulation of the blood which approached that demonstrated by Harvey. A leading systematic botanist. De Plantis, 1583. *Cf.* Oliver.

Chamberlin, Thomas Chrowder (1843—). Professor of geology, University of Chicago. Geologist with the Peary Relief Expedition, 1894; U. S. Geologist in charge of glacial division. The Origin of the Earth, 1916; The Terminal Moraine of the Second Glacial Period, 1883.

Chambers, Robert (1802-1871). Scotch author and publisher. Vestiges of the Natural History of Creation, 1844, 12th ed., 1884. *Cf.* Introduction to Vestiges, 12th ed., by A. Ireland, announcing Chambers as the author.

Charpentier, Johann von (1786-1855). Son of the mineralogist, Wilhelm von Charpentier. Student and follower of Werner. One of the founders of glacial research in Switzerland. Essai sur les Glaciers, 1841. *Cf.* Zittel, and Geikie.

Clairaut, Alexis Claude (1713-1765). French mathematician. A youthful prodigy; at the age of sixteen published his Recherches sur les courbes à double courbure, which secured for him admission to the Academy of Sciences. Later published Theorie de la figure de la Terre, which contained the celebrated "Clairaut's theorem."

Clausius, Rudolf Julius Emmanuel (1822-1888). German physicist. Studied at Berlin and Halle. Professor at Berlin, Zurich, Würzburg, and Bonn. Did important work in electrolysis and thermodynamics, and founded the kinetic theory of gases. Announced the Second Law of Thermodynamics, now one of the most firmly established of all scientific generalizations.

Columbus, Mathew Realdus (1516-1557). Italian anatomist. Temporary successor of Vesalius as professor at Padua. *Cf.* Foster, and Garrison.

Conybeare, William Daniel (1787-1857). Studied at Oxford; entered the Church and became Dean of Llandaff. Outlines of the Geology of England and Wales (with Phillips), 1822, the first widely used treatise on the subject in the English language.

Cope, Edward Drinker (1840-1897). Professor at Haverford, and Pennsylvania. Paleontologist of the U. S. Geological Survey. The Vertebrata of the Tertiary Formations of the West, 1883; Origin of the Fittest, 1886. *Cf.* Leading American Men of Science, edited by D. S. Jordan, 1910.

Copernicus, Nicolaus (1473-1543). Born in Thorn on the Vistula. Author of De Revolutionibus, which expounds the true planetary system. *Cf.* Biography by Prowe, Berlin, 1883.

Cordier, Pierre Louis Antoine (1777-1862). French mining engineer who took part in the Egyptian Expedition, 1819. Later professor of geology at the Botanical Garden. At the Restoration of the Empire he was made a peer of France. *Cf.* Zittel.

Cordus, Valerius (1515-1544). German botanist, son of the botanist Euricius Cordus. Studied at Wittenberg and later lectured there.

First to break away from the botany of the ancients. Historia Plantarum, 1563. *Cf.* Greene.

COTES, ROGER (1682-1716). English mathematician and philosopher. Professor of experimental philosophy at Cambridge. Published a second edition of Newton's "Principia." Harmonia Mensurarum, 1722.

COTTA, BERNHARD VON (1808-1879). Professor of geology at Freiburg. Rocks Classified and Described: a treatise on lithology, trans. by P. H. Lawrence, 1866.

COULOMB, CHARLES AUGUSTIN (1736-1806). French engineer and physicist. Had a military education. Chief researches were in electrostatics, but did notable work also in friction and elasticity.

CROOKES, WILLIAM, SIR (1832-1919). English chemist and physicist. Investigator of the rare earths, inventor of the Crookes tube, and proponent of the theory of "radiant matter" which led to the modern electron theory.

CURIE, MARIE SKLODOWSKA (1867—). Polish-French physico-chemist. Discovered (with her husband) radium. Recipient of Nobel prize.

CUVIER, GEORGES, BARON DE (1769-1832). Leading French naturalist of his time. Founder of comparative anatomy and vertebrate paleontology. Favorite of Napoleon Bonaparte. Director of higher education in the Empire. Leçons d'anatomie comparée, 1800; Le regne animal, 1817; Recherches sur les ossemens fossiles, 1812. *Cf.* Locy, and Russell.

DALTON, JOHN (1766-1844). English chemist and physicist. Inseparably associated with the atomic theory. New System of Chemical Philosophy, 1808.

DANA, JAMES DWIGHT (1813-1895). Geologist, mineralogist, and zoologist. Graduated from Yale in 1833. Geologist of the Wilkes Expedition, 1838. Professor of geology at Yale, 1850-1895. "His reports on geology of Pacific Ocean, volcanoes of Sandwich Islands, and coral reefs, as well as his comprehensive works on Zoophytes and Crustaceans, are among the finest productions in literature of scientific travel." Textbook of geology, 1863 (several editions). On denudation in the Pacific, 1850; On the degradation of the rocks of New South Wales and formation of valleys, 1850. *Cf.* Jordan, and Zittel.

DARWIN, CHARLES (1809-1882). The greatest biologist. Graduate of Cambridge, England. Voyage of the Beagle, 1844; Origin of Species,

1859; Descent of Man, 1871; Expression of the Emotions in Man and Animals, 1873; See Life and Letters, by his son, 1887. *Cf.* Judd.

DARWIN, ERASMUS (1731-1802). Highly successful country physician, poet, and naturalist. Fellow of the Royal Society. Grandfather of Charles Darwin. Botanic Garden, 1791. Zoonomia, 1794-1796; Phytologia, 1800; Temple of Nature, 1802. *Cf.* E. Krause and C. Darwin, Life of Erasmus Darwin, 1879.

DARWIN, GEORGE HOWARD, SIR (1845-1892). English mathematician, son of Charles Darwin. Important papers on the application of the theory of tidal friction to the evolution of the solar system, 1875.

DAUBRÉE, GABRIEL AUGUST (1814-1896). Mining engineer, and professor of mining and geology, Strassburg, 1861. Professor of geology, Museum of Paris. Carried on a brilliant series of experimental researches. *Cf.* Zittel.

DAVIS, WILLIAM MORRIS (1850—). American geographer and geologist. Professor of geology at Harvard University. Geographical Essays, 1909; Physico-geographie (with G. Braun), 1911.

DAVY, HUMPHRY, SIR (1778-1829). English chemist. Pioneer work in electrochemistry; inventor of the miner's safety lamp.

DESARGUES, GIRARD (1593-1662). French mathematician. Engineer and architect of Lyons; made important researches in geometry. Treated curve sections as projections of circles, and from it developed the theory of involution and of transversals, the fundaments of projective geometry.

DESCARTES, RENÉ (1596-1650). French philosopher and mathematician. Educated for the army, saw service in Holland. Gave up military career in 1621, and thereafter devoted himself to his favorite studies. Invented analytic geometry in 1637 when he published Discourse on the Method of Good Reasoning and of Seeking Truth in Science. Sought after universal mathematical science. Collected works, Paris, 1724-1729.

DESHAYES, PAUL (1797-1875). French geologist and conchologist. Studied medicine at Strassburg and Paris, but never practiced; was appointed professor of conchology at the Museum in Paris, 1869. Traité élémentaire de conchyliologie, 1839-1858. Mollusques de l'Algeria, 1848.

DESMAREST, NICHOLAS (1725-1815). French geologist. Disclosed significance of extinct volcanoes which made Auvergne famous. First to

teach clearly doctrine of origin of valleys by erosive action of streams. Published essay on subject accompanied by geological map, 1774. *Cf.* Geikie.

DEWAR, JAMES, SIR (1842-1923). British chemist. Known for his work on the liquefaction of gases; inventor of the vacuum-jacketed vessel.

DIOPHANTUS (third century A. D.). Greek algebraist. Was last and most fertile mathematician of second Alexandrian School. Chief work was Arithmetica which, excepting the Ahmes papyrus, was the earliest treatise on Algebra. His Porisms, and Polygonal Numbers were lost. *Cf.* H. Hankel and M. Cantor, History of Mathematics.

DIOSCORIDES, PEDANIOS (*c.* 64 A. D.). A learned Greek physician who traveled extensively. Wrote the 'botany' which was standard for fifteen centuries. First printed edition of his works appeared at Venice in 1499. Later editions and translations almost innumerable. *Cf.* Greene.

DODOENS, REMBERT (1517-1585). Physician to Emperor Maximilian II; professor at Leyden. Stirpium historiæ pemptades VI. *Cf.* A. Arber.

DOLLOND, JOHN (1706-1761). Constructed the first achromatic telescope; invented the heliometer. *Cf.* Clerke.

DONDERS, FRANS CORNELIUS (1818-1889). Student of physiological optics. Professor at Utrecht. First to measure the reaction time of a psychical process, 1868. Life by J. Moleschott, 1888. *Cf.* Stirling, and Garrison.

DUBOIS-REYMOND, EMIL (1818-1896). Student of and successor to J. Müller at Berlin. Established modern electro-physiology. Untersuchungen über thierische Electricität, 1841-1860. *Cf.* Garrison.

DUMAS, JEAN BAPTISTE ANDRÉ (1800-1884). French chemist. Best known for his work on the type theory, on vapor density and atomic weights.

EINSTEIN, ALBERT (1879—). German physicist. Studied in Munich, and then went to Switzerland. There he became naturalized, and was an engineer in the patent office, 1902-1909. Was later professor successively at Zürich, Prague, and Berlin. Great work was the development of the theory of relativity, and the generalized theory of gravitation. *Cf.* Pierpont.

EMPEDOCLES OF AGRIGENTUM (495-435 B. C.). "Father of the evolution idea." *Cf.* Osborn, and Clodd.

Eratosthenes (276-196 B. C.). Greek astronomer. First to measure the size of the earth.

Euclid (365 B. C.). Greek mathematician. Founded the first Alexandrian School. Published first book on geometry, The Elements. Took material from earlier mathematicians, but carefully selected and arranged the most important propositions from a few definitions and axioms. Was the greatest systematizer of his time. *Cf.* A. de Morgan, Euclides, in Smith's Dictionary of Greek and Roman Biography and Mythology.

Euler, Leonhard (1707-1783). Swiss mathematician. Spent most of his life at the courts of St. Petersburg and Berlin. Improved the theory of the moon and of the planets, invented the method of variation of elements. Introductio in analysis infinitorum, 1748; Institutiones calculi differentialis, 1755; Institutiones calculi integralis, 1768-1770. *Cf.* Rudis, Leonhard Euler; M. Cantor, Geschichte der Mathematik.

Fabricius, Hieronymus (1537-1619). Student of Falloppius and his successor at Padua. Learned surgeon and anatomist. Harvey's teacher. *Cf.* Curtis.

Falloppius, Gabrielus (1523-1563). Called from Pisa to Padua to occupy the chair of anatomy resigned by Vesalius. An able anatomist. Name preserved in the Falloppian canal and Falloppian tubes. See Foster, and Garrison.

Faraday, Michael (1791-1867). British chemist and physicist. After a common school education, he took up the bookbinder's trade. Attended Davy's lectures on natural philosophy, and later was associated with him in the Royal Institution. His experimental researches in electricity and magnetism (1841-1855) furnished the foundation for the work of Maxwell. Director of Royal Institution, 1825. *Cf.* Bruce Jones's Life and Letters of Faraday.

Fermat, Pierre de (1601-1665). French mathematician and scholar. Studied law at Toulouse, was made councillor for parliament of Toulouse. Devoted leisure time to mathematics. First to introduce infinitely small differences between two consecutive values of a function. Researches in the theory of numbers and probabilities entitle him to rank as the founder of the modern theory. De maximus et minimus; Opera mathematica, 1670.

Fischer, Emil (1852-1919). German chemist. Notable for work

on the synthesis of sugars, compounds of the purin group, and proteins.

Flamsteed, John (1646-1719). First Astronomer Royal of Great Britain. Founded the Greenwich Observatory; accumulated enormous amount of accurate data. Biography by Baily, London, 1835.

Fouqué, Ferdinand André (1828-1904). French geologist and petrologist. Professor of natural history, Collège de France; stratigraphical geologist of the Geological Survey. Santorin et ses eruptions, 1879; (with Michel-Lévy) Minéralogie micrographique, Roches eruptives francaises, 1879; Synthèse des minéraux et des roches, 1882.

Fourier, Jean Baptiste Joseph (1768-1830). French mathematician and statesman. Accompanied Napoleon on the Egyptian expedition, 1798. Professor at the École Normale, and École Polytechnique. Chief work was in heat, and his Théorie analytique de la chaleur (1822) is the classic of the subject. *Cf.* Arago's Biography of Fourier, in Smithsonian report of 1871.

Fraunhofer, Joseph (1787-1826). Improved construction of refracting telescopes; mapped the solar spectrum.

Fresnel, Augustin Jean (1788-1827). French engineer and physicist. Studied at École Polytechnique and the École des Ponts et Chaussées. His chief work was in optics: wave theory and the investigation of polarized light, diffraction, and interference. *Cf.* Duleau's Notice sur Fresnel, Revue encycl., t. 39.

Füchsel, G. Christian (1722-1773). Studied at Jena, Leipzig, and Erfurt; practiced medicine at Rudolstadt. Historia terræ et maris ex historia Thuringiæ permontium descriptionem erecta, Acta Acad. elect. Moguntinæ, 1762. Entwurf zur ältesten Erd und Menschen Geschichte, 1773. *Cf.* Zittel.

Galen, Claudius (*c.* 131-201). Greatest Greek physician after Hippocrates. Traveled extensively and finally settled in Rome. Practiced medicine and lectured on anatomy. Returned to Greece where he died. His work on anatomy and physiology the standard for fifteen centuries. Opera Omnia, edited by C. G. Kuhn, 20 vols. 1821-1833. Most famous single treatise is De Usu Partium, the original "natural theology." *Cf.* Foster, and Garrison.

Galilei, Galileo (1564-1642). Italian astronomer and physicist. Studied at Florence and Pisa. First applied the telescope to the sky, discovered sun spots, the rotation of the sun, lunar formations, satellites of

Jupiter, and phases of the planets. He endorsed the Copernican ideas and was twice tried by the Inquisition. *Cf.* Viviani's Life of Galileo, in Albéri's edition of Galileo's works, 1842-1856.

Galton, Francis, Sir (1822-1911). English student of heredity and founder of the eugenics movement. Cousin of Charles Darwin. Natural Inheritance, 1889. *Cf.* Memories, 1909.

Gascoigne, William (1620-1644). British astronomer. Invented the micrometer.

Gauss, Karl Friedrich (1777-1855). German mathematician. Director of the observatory at Göttingen. Disquisitiones Arithmetica, a treatise on the theory of numbers which contained the law of quadratic reciprocity and the theory of consequences. Invented imaginary numbers and method of least squares. Improved determination of orbits.

Gay-Lussac, Joseph Louis (1778-1850). French chemist. Best known for his law (1802) relating the volume and temperature of a gas (sometimes called the law of Charles, who had noted it 15 years earlier), and for his law (1809) of gaseous combining volumes.

Gegenbaur, Carl (1826-1903). German comparative anatomist. Professor of anatomy at Heidelberg. Emphasized comparative morphology, rather than embryology, as the criterion of homology. Untersuchungen zur vergl. Anatomie d. Wirbelthiere, 1864-1872. *Cf.* Russell.

Geoffroy Saint-Hilaire, Étienne (1772-1844). Colleague of Lamarck at the Jardin des plantes. Philosophical anatomist and teratologist. Philosophie anatomique, 1818. *Cf.* Osborn.

Gerhardt, Charles Frédéric (1816-1856). French chemist. Contributed towards correct methods of formulation of organic compounds.

Gesner, Conrad (1516-1565). Swiss polyhistor. Graduated in medicine at Basel. Professor of Greek at Lausanne, and later of Natural History at Zurich. Died from the plague, contracted through his duties as public physician. Almost equal attainments in bibliography, the languages, botany, and zoology. *Cf.* Locy; Miall's Early Naturalists; Brooks' Conrad Gesner, Pop. Sci. Mo., 1885.

Gibbs, Josiah Willard (1839-1903). American mathematician and physicist. Studied at Yale, Paris, Berlin, and Heidelberg. Professor of mathematical physics in Yale University. First to give a systematic treatment of chemical equilibrium on the basis of thermodynamics. Classic paper on The equilibrium of heterogeneous substances, 1876-1878. *Cf.*

H. A. Bumstead's biographical note in The Scientific Papers of J. W. Gibbs; Jordan.

Gilbert, Grove Karl (1843-1918). Graduated from the University of Rochester. Geologist of Ohio State Survey. *Cf.* W. C. Mendelhall: Memorial of Grove Karl Gilbert, Bull of Geol. Soc. of America, 1920.

Gilbert, William (1544-1603). British physicist. Studied at Cambridge. Physician to Queen Elizabeth and King James. His principal work was in magnetism, but also contributed to chemistry. De magnete, 1600, was the first physics paper of importance published in England. *Cf.* Sylvanus Thompson's Gilbert of Colchester, Father of Electrical Science, 1903.

Goethe, Johann Wolfgang von (1749-1832). Greatest poet of evolution. Gott und Welt; Versuch die Metamorphose der Pflanzen zu erklären, 1790. *Cf.* Osborn, Russell, and Sachs.

Graaf, Regnier de (1641-1673). Dutch physician, physiologist, and embryologist. De natura et usu succi pancreatici, 1664; Opera Omnia, 1677.

Graham, Thomas (1805-1869). British chemist. Noted for his work on diffusion and on colloids.

Gray, Asa (1810-1888). Professor of botany at Harvard, and for a generation the foremost American botanist. Manual of Botany; review of Darwin's Origin of Species, Am. Journal of Science and Arts, 1860; *Cf.* biography by J. M. Coulter in Leading Am. Men of Science, D. S. Jordan, editor, 1910.

Grew, Nehemiah (1641-1712). Student at Cambridge and Leyden, practicing physician in London. Secretary of the Royal Society. The Anatomy of Vegetables begun 1672; The Anatomy of Plants, 1682. *Cf.* A. Arber, Nehemiah Grew, in Oliver's Makers of British Botany.

Guettard, Jean Étienne (1715-1786). Studied medicine at Paris; later accompanied the Duke of Orleans on his travels. His discovery of extinct volcanoes at Auvergne (1752) gave new impulse to mineralogical study of volcanic rocks in that vicinity. First to publish detailed investigation of fossil sponges. *Cf.* Zittel, and Geikie.

Guldberg, Cato Maximilian (1836-1902). Norwegian mathematician. Discoverer, with Waage, of the law of mass-action.

Haeckel, Ernst (1834-1919). Professor of zoology at Jena. Chief

early supporter of Darwinism in Germany. Generelle Morphologie, 1866. See Bölsche, Life and Works, 1906.

Hales, Stephen (1677-1761). Fellow of Cambridge, and later Curate of Teddington. Founder of plant physiology as an experimental science. Vegetable Staticks, 1727; Haemostaticks, 1733; *Cf.* F. Darwin, Stephen Hales, in Oliver's Makers of British Botany.

Hall, James (1761-1832). Scotch geologist and physicist. Established experimental research as an aid to geological investigation. *Cf.* Zittel, and Geikie.

Hall, Marshall (1790-1857). English physiologist. The Reflex Function of the Medulla Oblongata and Medulla Spinalis, 1833; Memoirs by C. Hall, 1861.

Haller, Albrecht von (1708-1777). Educated at Bern and Tübingen. Graduated in medicine at Leyden. Professor of anatomy, botany, and medicine at Göttingen until he retired to his native city, Bern. Elementa Physiologiæ, 1757-1765. *Cf.* Foster.

Halley, Edmund (1656-1742). English astronomer. Predicted the return of a comet; discovered terrestrial magnetism, the secular acceleration of the moon, and the proper motions of stars.

Hamilton, William Rowan, Sir (1805-1865). Scotch mathematician. Professor of astronomy at Dublin. Quaternions, 1844; On a General Method in Dynamics; and Principle of Varying Action. *Cf.* R. P. Greaves, Life of Sir W. R. Hamilton, 1882-1903.

Harvey, William (1578-1657). Graduate in arts of Cambridge, and in medicine of Padua under Fabricius. Physician to King Charles I. Lecturer on anatomy at the London College of Physicians, where he expounded his discoveries over a decade before publication. Exercitatio Anatomica de Motu Cordis et Sanguinis in Animalibus, 1628; Exercitationes de Generatione Animalium, 1651. *Cf.* J. G. Curtis, Harvey's Views on the Use of the Circulation of the Blood, 1915; T. H. Huxley, William Harvey, 1878, in Collected Scientific Memoirs; R. Willis, William Harvey, 1878.

Haüy, René Just (1743-1822). French mineralogist. Discovered the geometrical law of crystallization; also known for his observations in pyro-electricity. Traité de minéralogie, 1801.

Helmholtz, Hermann Ludwig Ferdinand von (1821-1894). German philosopher and scientist. Studied medicine at Berlin, and was,

for a time, an army surgeon. Professor of physiology at Königsberg, Bonn, and Heidelberg; professor of physics at Berlin. Work in optics, and sound; but especially in theoretical physics. Über die Erhaltung der Kraft, 1847. *Cf.* L. Königsberger's Hermann von Helmholtz, translated by F. A. Welby, 1906.

Helmont, Jean Baptiste van (1577-1644). Graduate in medicine at Louvain. Lived near Brussels. Devoted his life to chemical studies, and incidentally practiced medicine as a charity. Ortus medicinæ, 1648. *Cf.* Foster.

Henry, Joseph (1797-1878). American physicist. One of the first Americans to reach high eminence as an original investigator in physical science. Professor of natural philosophy at Princeton; first secretary of the Smithsonian Institution. *Cf.* Simon Newcomb's Life of Henry in Leading American Men of Science, edited by D. S. Jordan, 1910.

Herschel, John, Sir (1792-1871). Son of William Herschel; extended his father's surveys to the south pole of the heavens. Studied amount of heat received from the sun on a given area of earth. *Cf.* biography by A. M. Clerke.

Herschel, William, Sir (1738-1822). German musician who emigrated to England. Completed several surveys of all the sky visible from England; catalogued eight hundred stars and two thousand nebulæ; discovered the binary character of double stars; determined the sun's motion in space. *Cf.* Life and Works, by Holden, 1881; The Herschels and Modern Astronomy by A. M. Clerke, 1895.

Hertz, Heinrich Rudolf (1857-1894). German physicist. Civil engineer, and later professor at Karlsruhe and Bonn. Chief work was in the theory of electric waves. *Cf.* preface to his collected papers, edited by D. E. Jones.

Hill, George William (1838-1914). American astronomer, known for his investigations on the orbits of the four outer planets and of the moon; devised the method of periodic orbits.

Hipparchus (*c.* 150 B. C.). Greek astronomer. The greatest astronomer of antiquity. Constructed tables of the sun; discovered the principal inequality in the motion of the moon; compiled the first catalog of star positions; discovered the precession of the equinoxes; founded trigonometry. Scientific geography originated with his invention of the method of fixing terrestrial positions of circles of latitude and

longitude. Only work to survive, Commentary on the Phenomena of Aratus and Eudoxus, published by P. Victorius, Florence, 1567. *Cf.* J. B. J. Delambre, Histoire de l'astronomie ancienne.

HIPPOCRATES (460-370 B. C.). Greek philosopher and "Father of Medicine." Studied medicine under his father, Heraclides, and Herodicus; philosophy under Gorgias and Democritus. Traveled extensively. Taught and practiced in Athens, Thrace, Thessaly, Delos, and Cos. Born of a family of priest-physicians and was first to cast superstition aside and base the practice of medicine on principles of inductive philosophy. Gave attention to nature and history of the disease. First to emphasize principles of public health. *Cf.* Adams, The Genuine Works of Hippocrates; Œuvres complètes d'Hippocrate, traduction nouvelle, par E. Littré, 1839-1861; F. H. Garrison.

HITCHCOCK, EDWARD (1793-1864). Professor of chemistry and natural history at Amherst College. One of the founders of American geology. Geology of the Connecticut Valley, 1823; Fossil Footmarks in the United States, 1848; Outline of the Geology of the Globe and of the United States in particular, 1853; The Religion of Geology and its Connected Sciences, 1851.

HOFF, JACOBUS HENDRICUS VAN'T (1852-1911). Dutch chemist, known for his work on stereochemistry, and on equilibrium in solutions.

HOFMANN, AUGUST WILHELM (1818-1892). German chemist, who (while in England), with his pupils, brought the coal-tar dye industry into existence.

HOOKE, ROBERT (1635-1703). English physicist, mathematician, and naturalist. One of the most brilliant thinkers of any age. First to suggest that fossils could be used in revealing the earth's historical past. Coined the biological term 'cell.' Micrographia, 1665; Posthumous Works, R. Waller, editor, 1705. *Cf.* L. L. Woodruff, Hooke's Micrographia, Amer. Naturalist, 53, 1919.

HOOKER, JOSEPH DALTON, SIR (1817-1911). Graduated at Glasgow. Foremost English systematic and philosophical botanist during the Darwinian period. Flora of British India, 1872-1897. *Cf.* Oliver.

HUGGINS, WILLIAM, SIR (1824-1910). English astronomer. Pioneer in astronomical spectroscopy; detected the gaseous nature of nebulæ.

HUNTER, JOHN (1728-1793). Studied under his brother William, and, like him, was a leading London surgeon. Described the anatomy of

some 500 species of animals. Founder of experimental and surgical pathology and a pioneer in comparative physiology and experimental morphology. Works of John Hunter, 1835. *Cf.* S. Badget's Life of John Hunter, 1897, Garrison, and Stirling.

HUTTON, JAMES (1726-1797). Scotch geologist. Studied at Edinburgh, Paris, and Leyden. Founder of physical and dynamic geology. Paper on Theory of the Earth read before Royal Society of Edinburgh, 1785; published in Transactions, 1788. Revised work appeared in 2 vols., 1795. *Cf.* Zittel, Geikie, and Judd.

HUXLEY, THOMAS HENRY (1825-1895). English anatomist, essayist, and protagonist of evolution. Collected Scientific Memoirs; Collected Essays. *Cf.* Life and Letters, edited by his son, 1901.

HUYGENS, CHRISTIAN (1629-1695). Dutch physicist and astronomer. Studied at Leyden and Breda. Spent most of his life in Paris. Did important work in mechanics and astronomy, but is known chiefly for his investigations in the wave theory of light. Traité de la lumière, 1678. *Cf.* preface to his Opera varia, 1722.

INGEN-HOUSZ, JAN (1730-1799). Dutch physician who practiced in London. Basic contributions to photosynthesis. On the Nutrition of Plants and the Fruitfulness of the Earth, 1796. *Cf.* Sachs.

JACOBI, KARL GUSTAV JACOB (1804-1851). German mathematician. Studied at Berlin; professor at Königsberg. Gave theory of elliptic functions a new basis, especially in his development of the theta-functions in his Fundamenta nova theoriæ functionum ellipticarum. *Cf.* Lejeune-Dirichlet's Gedächtnisrede auf Jacobi, 1852.

JAMESON, ROBERT (1774-1854). Professor of geology at Edinburgh for fifty years. Elements of Geognosy, 1808. *Cf.* Geikie.

JOULE, JAMES PRESCOTT (1818-1889). British physicist. Mainly self-taught, but was for a time under the guidance of John Dalton. The calorific effects of magneto-electricity and the mechanical value of heat, 1843. *Cf.* The free expansion of gases, edited by J. S. Ames, 1898.

JUNG, JOACHIM (1587-1657). Professor at Giessen, Lübeck, and Helmstädt. Botanist and philosopher. Doxoscopiæ physicæ minores, 1662; Isagoge phytoscopica, 1678. *Cf.* Sachs.

KEKULÉ, FRIEDRICH AUGUST (1829-1896). German chemist, who promulgated the doctrine of the linking of atoms and conceived and established the closed-chain or ring theory of the constitution of benzene.

Kelvin, William Thomson, Lord (1824-1907). British physicist. Studied under his father, James Thomson, and at the Universities of Belfast, Cambridge, and Paris. Professor of natural philosophy at Glasgow for 53 years. Investigations in thermodynamics, electricity, mechanics, hydrodynamics. Invented many valuable instruments. *Cf.* Andrew Gray's Lord Kelvin.

Kepler, Johann (1571-1630). German mathematician and astronomer. Succeeded Tycho Brahé at Prague as Imperial Mathematician. Studied volumes of solids; revolutionized astronomy by the discovery of the three laws of planetary motion. Astronomia nova. *Cf.* Sedgwick and Tyler.

Kirchhoff, Gustav Robert (1824-1887). German physicist. Best known for his development (with Bunsen) of the method of spectrum analysis.

Koch, Robert (1843-1910). Greatest German bacteriologist. Graduate in medicine at Göttingen, professor of hygiene and bacteriology in Berlin. Demonstrated the causal relation of various bacteria to disease; established modern bacteriological methods. Untersuchungen über die Aetiologie der Wundinfektionskrankheiten, 1878. *Cf.* Garrison.

Lacaze-Duthiers, Henri (1821-1901). Director of the biological stations at Roscoff and Banyuls. Founder of the French journal of experimental zoology. *Cf.* Locy.

Lacroix, Antoine François Alfred (1863—). Professor of mineralogy at the Jardin des Plantes and in the École des Hautes Études. (With Michel-Lévy) Les minéraux des roches, 1888, and Tableau des minéraux des roches, 1889. La Montagne Pelée et ses éruptions, 1904. Minéralogie de la France et de ses Colonies, 1893-1898. *Cf.* Zittel.

Lagrange, Joseph Louis, comte de (1736-1813). French mathematician. Professor at Berlin and Paris. Made important mathematical contributions. Known principally for his Mécanique analytique, 1788. *Cf.* Œuvres de Lagrange.

Laguerre, Edmond (1834-1886). French mathematician. Professor in the Collège de France. Chief work was in the theory of equations, based on Descartes' rule of signs, in assigning an upper limit to the number of real roots of a polynomial with real coefficients after developing it into a power series within a certain interval.

LALANDE, JOSEPH JEROME (1732-1807). French astronomer. Constructed the first extensive catalog of faint stars. Histoire céleste, 1801.

LAMARCK, JEAN BAPTISTE DE (1744-1829). Botanist, zoologist, evolutionist of the Jardin des Plantes. Philosophie zoologique, 1809, English trans. by H. Elliot, 1914. *Cf.* A. S. Packard, Lamarck, the Founder of Evolution, 1901; Butler, Evolution Old and New, 1911.

LAPLACE, PIERRE SIMON (1749-1827). French mathematician and astronomer. Professor at École Militaire of Paris. President of the Bureau of Longitude, aided in organization of the decimal system. Gained political honors under Napoleon; chancellor of the senate, and grand officer of the Legion of Honour. Méchanique céleste, second only to Newton's Principia, contained the important "Laplace's equation" and other theorems pertaining to celestial mechanics. *Cf.* Fourier's Éloge, Mémoirs de l'institute, 1831.

LAVOISIER, ANTON LAURENT (1743-1794). French chemist, the father of scientific chemistry. Guillotined during the French Revolution. Sur la nature du principe, etc., 1775; Traité élémentaire de chimie, 1789. *Cf.* Foster.

LEEUWENHOEK, ANTONY VAN (1632-1723). Enjoyed no educational advantages. Held a minor town office in Delft and devoted his leisure to his lenses. Opera Omnia (collected letters to scientific societies), 1687-1719; Select Works, edited by S. Hoole, 1800-1807. *Cf.* B. W. Richardson, Disciples of Æsculapius, 1900, and Miall, Early Naturalists.

LEGENDRE, ANDRIEN MARIE (1752-1833). French mathematician. Professor at École Militaire, Paris. Chief work was elliptic integrals, especially with the gamma-functions, theory of numbers, attraction of ellipsoids, and least squares. Wrote Éléments de géométrie, accepted on the continent as a substitute for Euclid. *Cf.* Élie de Beaumont, Memoir de Legendre, trans. by C. A. Alexandrea, Smithsonian Report, 1874.

LEIBNITZ, GOTTFRIED WILHELM (1646-1716). German philosopher, mathematician, and man of affairs. Studied law at Leipzig, mathematics at Jena. Was elector of Mainz, moved to Hanover and gave his service to the Brunswick family. In 1675 invented the notation of calculus and sign of equality. Shared with Newton the honor of inventing calculus. His work was published in 1686 in the Acta eruditorum. *Cf.* C. J. Gerhardt, Mathematics, 3d series, Berlin, 1849-1863.

LEIDY, JOSEPH (1823-1891). One of the pioneers of American verte-

brate paleontology and protozoology. Professor of anatomy at the University of Pennsylvania. Mammalian Remains of Nebraska, 1853; Fresh water Rhizopods of North America, 1879. *Cf.* H. F. Osborn, Biography of Leidy, in Nat. Acad. Sci. Biog. Memoirs, 1913.

LEONHARD, K. C. VON (1779-1862). Professor of mineralogy and geology at the University of Heidelberg. Charakteristik der Felsarten, 1823.

LEVERRIER, URBAIN JEAN JOSEPH (1811-1877). French astronomer and mathematician. Shared with Adams the discovery of Neptune by its effect on Uranus.

LIE, MARIUS SOPHUS (1842-1899). Norwegian mathematician. Professor at Christiania and Leipzig. Aimed to advance the theory of differential equations, and with this in view developed the theory of transformation groups. Theorie der Transformations gruppen, 1888-1893. *Cf.* Bibliotheca Mathematica, 1900.

LIEBIG, JUSTUS VON (1803-1873). German chemist. Professor at Giessen. Founder of agricultural chemistry and the first to give a broad survey of the chemistry of organisms. Die organische Chemie in ihrer Anwendung auf Agricultur und Physiologie, 1840. *Cf.* Sachs.

LINNÆUS, CAROLUS (1707-1778). Most influential botanist of the eighteenth century. Studied at Lund and Upsala, Sweden; graduated in medicine at Harderwyck. Professor of botany at Upsala. His collections and library preserved by the Linnean Society of London. Established the binomial nomenclature in biological classification. Systema Naturæ, 1735, 10th edition, 1758; Species Plantarum, 1753. *Cf.* Sachs.

LOBATCHEWSKI, NICHOLAS IVANOVICH (1793-1856). Russian mathematician. Professor at Kazan. Pioneer in non-Euclidian geometry. Pangeometrie, 1855. *Cf.* F. Engel, N. I. Lobachewsky, 1899.

LOCKYER, NORMAN (1836-1920). British astronomer. Pioneer in stellar spectroscopy, observed solar prominences without an eclipse, and studied chemical composition of these prominences.

LOGAN, WILLIAM EDMOND (1798-1875). Canadian geologist. Educated at the University of Edinburgh. In 1842 he took charge of the newly established geological survey in Canada. Made notable researches on the coal-strata and an excellent geological map of Canada. *Cf.* Geikie, and Zittel.

LOWER, RICHARD (1631-1690). English anatomist and physiologist.

Educated at Oxford; practiced medicine in London. Tractus de corde, 1669. *Cf.* Foster.

LUDWIG, CARL (1816-1895). Professor at Marburg, Zürich, Vienna, and Leipzig. Applied the graphic method to physiological study. *Cf.* Stirling.

LYELL, CHARLES, SIR (1797-1875). Foremost British geologist of the nineteenth century. Son of a wealthy proprietor of Scotland. Graduated at Oxford. Settled in London. Established uniformitarianism in geology. Principles of Geology, 1830-1833; Antiquity of Man, 1863. *Cf.* T. G. Bonney, Charles Lyell and Modern Geology, 1895; Life, Letters, and Journals of Sir Charles Lyell, Bart., edited by his sister-in-law, Mrs. Lyell, 1881; J. W. Judd, The Coming of Evolution, 1910.

LYONET, PIERRE (1707-1789). Dutch artist, linguist, and lawyer. Traité Anatomique de la Chenille qui ronge le bois de Saule, 1760. *Cf.* Locy, and Miall's Early Naturalists.

MACLAURIN, COLIN (1698-1746). Scotch mathematician. Professor at Aberdeen and Edinburgh. Was first to write on pedal curves. His treatise on Fluxions contained the correct way to distinguish between maxima and minima, and explained their use in the theory of multiple points. Wrote also on tides, and problems in mathematical physics and in mechanics.

MAGENDIE, FRANÇOIS (1783-1855). Professor at Paris. Emphasized modern experimental method in physiology. Phénomènes physiques de la Vie, 1842. *Cf.* Stirling.

MALPIGHI, MARCELLO (1628-1694). Italian biologist. Student at Bologna. Professor of Medicine at Pisa, Messina, and Bologna. De Bombyce, 1669; De Ovo incubato, 1672, and De formatione Pulli in ovo, 1673; Anatome Plantarum, 1675-1679; Opera Omnia, 1687. *Cf.* Foster, Sachs, and Miall's Early Naturalists.

MARSH, OTHNIEL CHARLES (1831-1899). Professor of paleontology at Yale University. Notable monographs on restorations of extinct vertebrates, especially the series of fossil horses. *Cf.* biography in Leading American Men of Science, edited by D. S. Jordan, 1910.

MATTIOLI, PIERANDREA (1501-1577). Italian botanist. Physician to Emperor Maximilian II. Commentarii in sex libros Pedacii Dioscoridis, 1544. *Cf.* A. Arber, Herbals.

MAXWELL, JAMES CLERK (1831-1879). British physicist. Educated

at Cambridge; professor at Marischal College, King's College, and at Cambridge. His greatest work was his Treatise on electricity and magnetism, 1873, but he obtained important results in a wide range of subjects in mathematical physics. *Cf.* A. Macfarlane's Ten British Physicists, 1919.

MAYER, JULIUS ROBERT (1814-1878). German physicist and physician. Studied medicine at Tübingen, Munich, and Paris. Traveled widely, and spent his spare time studying physiology. Chief work was in the theory of heat: Die Mechanik der Wärme, 1893. *Cf.* John Tyndall's appreciation in Philosophical Magazine, 1863.

MAYOW, JOHN (1643-1679). British investigator of animal respiration. Graduated in law at Oxford. Tractatus de sale nitro-, et spiritu nitro-aero, de respiratione, etc., 1668. *Cf.* Stirling, and Foster.

MECKEL, JOHANN FRIEDRICH (1781-1833). Pupil of Cuvier; professor at Halle. Probably the greatest German comparative anatomist before Müller. Beiträge zur vergleichende Anatomie, 1808-1812. *Cf.* Russell.

MENDEL, GREGOR JOHANN (1822-1884). Natural Science instructor and Abbot of a monastery at Brünn, Austria. Applied statistical methods in his study of the inheritance of characters in pedigree lines of sweet peas and formulated the Mendelian laws of inheritance. Versuch über Pflanzen-Hybriden, 1865. *Cf.* W. Bateson, Mendel's Principles of Heredity, with Translations of his Original Papers, 1902.

MENDELÉEFF, DMITRI IVANOVICH (1834-1907). Russian chemist, best known for his work on the classification of the chemical elements by means of the periodic law.

MICHEL-LÉVY, AUGUSTE (1844-1911). Inspector-general of mines, and director of the Geological Survey of France. Distinguished for his researches on eruptive rocks, their microscopic structure and origin. Structures et classification des roches éruptives, 1889; (with Lacroix) Les Minéraux des roches, 1888; (with Lacroix) Tableau des minéraux des roches, 1889; (with Fouqué) Minéralogie micrographique, 1879; (with Fouqué) Synthèse des minéraux et des roches, 1882.

MILNE-EDWARDS, HENRI (1800-1885). Professor at the Sorbonne. Emphasized physiological division of labor in the economy of the organism. Histoire Naturelle des Crustacés, 1834-1840; Leçons sur la Physiologie et l'Anatomie comparées, 1857-1880. *Cf.* Russell, and Locy.

Minkowski, Hermann (1864-1909). German mathematician. *Cf.* Gesammelte Abhandlungen von Minkowski, edited by D. Hilbert, 1911.

Moissan, Henri (1852-1907). French chemist. Pioneer in work with the electric furnace at high temperatures; isolated fluorine, which had resisted all previous efforts.

Moivre, Abraham de (1667-1754). French mathematician. Compelled to leave France on the revocation of the Edict of Nantes. Settled in London and gave lessons in mathematics. Discovered theorem known by his name in higher trigonometry; his work on the theory of probability ranks with that of Laplace. Doctrine of Chances; Miscellanea Analytica. *Cf.* D. Todhunter, A History of the Mathematical Theory of Probability, 1865.

Monge, Gaspard (1746-1818). French mathematician. Professor at Mézières, Lyceum and École Normale at Paris. Was inventor of descriptive geometry and gave many new and important methods to analytic geometry. *Cf.* Dupin, Éssai historique sur les services et les travaux scientifiques de Gaspard Monge, 1819.

Müller, Johannes (1801-1858). Studied theology and medicine at Bonn. Professor at Bonn and Berlin; wide influence as teacher and investigator; leading German physiologist of his time, and probably contributed more than any one else to the establishment of comparative physiology. Handbuch der Physiologie des Menschen, 1834-1840. *Cf.* P. B. Hadley, Life of Müller, Popular Science Monthly, 1908.

Murchison, Roderick Impey (1792-1871). British geologist. Notable investigations of the older Paleozoic rocks which culminated in the establishment of the Silurian system of formations. The Silurian System, 1839. *Cf.* Geikie's Life, 1875.

Napier, John (1550-1617). Scotch mathematician. The inventor of logarithms. Canonis descriptio, 1614.

Naumann, Carl Friedrich (1797-1873). German mineralogist and geologist. Professor of mineralogy and geognosy in University of Leipzig. Lehrbuch der geognosie, 1850.

Nernst, Walther (1864—). German physical chemist who has made many important contributions to the subject.

Newberry, John Strong (1822-1892). American geologist. Professor of geology and paleontology at Columbia University; paleon-

tologist to the United States Geological Survey. The origin and classification of ore deposits, 1880.

NEWCOMB, SIMON (1835-1909). American astronomer. Studied at Harvard. Professor at Johns Hopkins. Pre-eminent in the astronomy of position; made notable researches on the theory of the moon's motions; published tables of the planets; master in the comparison between theory and observations. *Cf.* Leading American Men of Science, edited by D. S. Jordan, 1910; Autobiography, 1903.

NEWTON, ISAAC, SIR (1642-1727). British scientist. Studied at Trinity College, Cambridge. Made fundamental contributions to mathematics, mechanics, optics, and astronomy. Discovered the law of gravitation, explained the tides, the figure of the earth, the chief perturbations in the solar system; constructed the first reflecting telescope. His chief work, the Philosophiæ naturalis principia mathematica, 1686, is regarded as the greatest single contribution to science. *Cf.* Memoirs of Sir Isaac Newton, edited by Brewster, Edinburgh, 1854.

ONNES, HEIKE KAMERLINGH (1853—). Dutch physicist, known for investigations at extremely low temperatures.

OSTWALD, WILHELM (1853—). German chemist whose teaching and writings have been influential in promulgating the general principles of chemistry.

OWEN, RICHARD, SIR (1804-1892). Hunterian Professor at the Royal College of Surgeons, and Head of the Natural History Department of the British Museum, London. Odontography, 1840-1845. On the Archetype and Homologies of the Vertebrate Skeleton, 1848; Anatomy and Physiology of the Vertebrates, 1866-1868; *Cf.* Life, edited by his grandson (including essay by Huxley on Owen's position in anatomical science), 1894.

PALISSY, BERNARD (1510-1589). French ceramic artist. In 1580 he published a book in which he discussed the origin of petrified wood, the occurrence of fossil fishes in Mansfield slate, and fossil molluscs in various rocks. *Cf.* Zittel, and Geikie.

PASTEUR, LOUIS (1822-1895). Graduated at the École Normale, Paris. Professor of chemistry at Strassburg, Lille, and the Sorbonne, and Director of the Pasteur Institute, Paris. Classical studies on fermentation and microorganisms. *Cf.* Life of Pasteur by R. Vallery-Radot, 1902.

PERKIN, WILLIAM HENRY, SIR (1838-1907). English chemist, discoverer in 1856 of mauve, the first aniline dye.

PEYER, JEAN CONRAD (1653-1712). Swiss physician. Studied at Basel and Paris. Exercitatio anatomica medica de glandulis intestinorum, 1677. *Cf.* Foster.

PHILLIPS, JOHN (1800-1874). Nephew of William Smith and guided by him into geological studies. Arranged the museum at York, London, Dublin, and Oxford. In 1834 he was appointed professor of geology at King's College, London; in 1844 at Dublin, and in 1856 he succeeded Buckland at Oxford. Geology of Yorkshire, 1832.

PIAZZI, GIUSEPPE (1746-1826). Italian astronomer. Discovered the first asteroid; compiled a catalog of many faint stars.

PICKERING, EDWARD CHARLES (1846-1919). American astronomer. Applied photography to the photometry of stars, and to their spectra; discovered the first spectroscopic binary.

PLANCK, MAX KARL ERNST LUDWIG (1858—). German physicist. Professor of mathematical physics at Berlin. Chief work is in thermodynamics and the radiation theory. The Theory of Heat Radiation, translated by M. Masius, 1914.

PLATO (429-348 B. C.). Greek philosopher and mathematician. Studied under Socrates and Theodorus; came in contact with the Pythagoreans. Traveled extensively. Founder of the Platonic School. Invented analysis as a method of proof.

PLAYFAIR, JOHN (1748-1819). Professor of mathematics and later of philosophy at Edinburgh. Exponent of Hutton. Illustrations of the Huttonian Theory, 1802. *Cf.* Zittel.

PLINY THE ELDER (23-79). Roman general and littérateur. Historia Naturalis, translation in Bohn's Library. *Cf.* Locy, and Miall.

POINCARÉ, HENRI (1854-1912). French mathematician. Professor at Caen and the Sorbonne. Contributed to mathematics, physics, astronomy, and philosophy. Most important researches in analysis, differential equations, theory of functions; discovered fuchsian and theta-fuchsian functions; enriched the theory of integrals. *Cf.* H. Poincaré, The Foundations of Science, trans. by G. B. Halstead; Ernest Lebon, Henri Poincaré, Biographie, 1909.

POISSON, SIMEON DENIS (1781-1840). French mathematician. Professor at the École Polytechnique, astronomer to the Bureau des Longi-

tudes. Chief work on the theory of elasticity, and on the theory of electricity and magnetism. *Cf.* I. Todhunter, History of the Theory of Elasticity, edited by Karl Pearson, 1886; and F. Argo, Biographie de Poisson, 1850.

PONCELET, JEAN VICTOR (1788-1867). French mathematician and engineer. Studied at École Polytechnique, and École de l'Application. Lieutenant of engineers in the Russian campaign and taken prisoner. While in prison made his original researches in projective geometry. Formulated the principle of continuity. Traité des Propriétés projectives des figures. *Cf.* J. Bertrand, Éloge historique de Poncelet, 1875.

POWELL, JOHN WESLEY (1834-1902). American geologist. Professor at Illinois Wesleyan University and the Normal University. His work led to the establishment of the U. S. geological and geographical survey of the Rocky Mountain region under his direction 1870-1879; Director of Bureau of Ethnology, 1879; and Director of the Geological Survey, 1881. Exploration of the Colorado River of the West and its Tributaries, 1875.

PRIESTLEY, JOSEPH (1733-1804). Clergyman at Leeds and Birmingham, England. Man of letters and science, theologian, politician. Experiments and Observations on Different Kinds of Air, 1775-1777. *Cf.* T. H. Huxley, Joseph Priestley, 1874 (Collected Essays); T. E. Thorpe, Joseph Priestley, 1906.

PTOLEMY OF ALEXANDRIA (*c.* 130 A. D.). Greek astronomer. Discovered the evection of the moon and atmospheric refraction. Also wrote on geography and optics; represented motion of planets with fair exactitude. Author of the Syntaxis or Almagest, which preserves the work of Hipparchus and others.

PYTHAGORAS (*c.* 580-500 B. C.). Greek mathematician of Samoa. Founded the Pythagorean School. He raised mathematics to the rank of science, and closely connected geometry and arithmetic.

QUENSTEDT, FRIEDRICH (1837-1889). Professor of geology and paleontology in Tübingen for more than fifty years. Petrefaktenkunde, 1852; 3d ed. 1885, for three decades the chief handbook of German students. Paleontology of Germany, 1874-1875.

RAMSAY, WILLIAM, SIR (1852-1916). British chemist, best known for his work (initially with Rayleigh) on the rare gases of the atmosphere.

RAOULT, FRANÇOIS MARIE (1830-1901). French chemist. Chiefly known for his work on the freezing temperature and vapor pressure of solutions.

RATHKE, MARTIN HENRY (1793-1860). Professor at Dorpat and Königsberg. Abhandlungen zur Bildungs- und Entwickelungs-Geschichte des Menschen und der Thiere, 1832-1833. *Cf.* Russell.

RAY, JOHN (1628-1705). British clergyman, botanist, and zoologist. Student and lecturer at Cambridge. Methodus Plantarum Nova, 1682. *Cf.* S. H. Vines' Essay, in Oliver.

RAYLEIGH, JOHN WILLIAM STRUTT, LORD (1842-1919). British physicist. Graduated from Trinity College, Cambridge. Cavendish professor of experimental physics from 1879 to 1884, and then became professor of natural philosophy in the Royal Institution. Made notable contributions to the theory of liquids and gases, sound, optics, electricity, elasticity. *Cf.* Sir Oliver Lodge's appreciation in National Review, 1898.

RÉAUMUR, RENÉ ANTOINE FERCHAULT (1683-1757). Studied at Poitiers, Bourges, and Paris. One of the most ingenious naturalists and physicists that France has produced. Mémoires pour servir à l'histoire des Insectes, 1734-1742; Sur la Digestion, 1752. *Cf.* Foster, and Miall's Early Naturalists.

REDI, FRANCESCO (1626-1698). Italian physician. Studied at Pisa. Made the initial experiments in the long controversy concerning Abiogenesis. Esperienze intorno alla generazione degl'insetti, 1668 (English trans. by M. Bigelow, 1909); Opera, 1712. *Cf.* Miall's Early Naturalists.

RHETICUS, GEORGE JOACHIM (1514-1576). German astronomer and mathematician. Professor at Wittenberg, and later associated with Copernicus. Opus Palatinum de Triangulis, 1596.

RIEMANN, GEORGE FREDERICK BERNHARD (1826-1866). German mathematician. Professor at Göttingen. Laid the foundation for a general theory of functions of a complex variable and applied the theory of potential to pure mathematics. Collected works, Leipzig, 1876.

ROEMER, OLAUS (1644-1710). Danish astronomer. Worked chiefly at Paris. Determined the velocity of light and invented the meridian circle.

RONDELET, GUILLAUME (1507-1566). Professor of anatomy at Montpellier. Attracted many students in natural history. Libri de Pisci-

bus Marinis, 1554; Universæ aquatilium Historiæ pars altera, 1555. *Cf.* Miall's Early Naturalists.

Roozeboom, Hendrik Willem Bakhuis (1855-1907). Dutch chemist best known for his systematic investigation and interpretation of heterogeneous chemical equilibria by means of the phase rule. *Cf.* Berichte der deutschen chemischen Gesellschaft, 1907.

Rosenbusch, Karl Harry Ferdinand (1836-1914). German geologist. Student at Freiburg. Professor of mineralogy and geology at Heidelberg University. Die mikroskopische Physiographie der petrographisch wichtigen Mineralien, Stuttgart, 1873; Die mikroskopische Physiographie der massigen Gesteine, 1877; Elementen der Gesteinslehre, 1898. *Cf.* Zeit. für Mineralogie, Geologie, und Paläontologie, 1914; E. A. Wülfing, Zur Erinnerung an Harry Rosenbusch, 1914.

Roth, Justus Ludwig Adolf (1818-1892). Professor of mineralogy at Berlin. One of the founders of petrographical science. Der Vesuv und die Umgebung von Neapel, 1857; Allgemeine und chemische Geologie, 1879-1893.

Rowland, Henry Augustus (1848-1901). American physicist. Student at Rensselaer Institute and Yale University. Professor of physics at Johns Hopkins University. Important investigations on the mechanical equivalent of heat; devised concave gratings for analysis of spectra. *Cf.* Leading American Men of Science, D. S. Jordan, editor.

Rumford, Benjamin Thompson, Count (1753-1814). American man of science, philanthropist, and founder of the Royal Institution of London. First to show (1798) that heat is a mode of motion. *Cf.* Jordan.

Rutherford, Ernest, Sir (1871—). British physicist. Studied at Canterbury College, N. Z.; and Trinity College, Cambridge. Professor at McGill University and later at Manchester. Outstanding work in radioactivity.

Rutherfurd, Lewis Morris (1816-1892). American amateur astronomer. First used photographs to determine positions of stars; constructed first photographic refractor.

Saussure, Horace Benedicte de (1740-1799). Noble family of high scientific repute. Professor of philosophy at Geneva 1787. In charge of first ascent of Mt. Blanc. Voyage dans les Alpes (1779-1796).

Saussure, Nicholas Théodore de (1767-1845). Son of the

famous explorer of the Alps. Spent his life in Geneva; refused university positions. Recherches chemiques sur la végétation, 1804. *Cf.* Sachs.

SCHLEIDEN, MATTHIAS JACOB (1804-1881). German botanist. Studied law at Heidelberg, medicine at Göttingen, botany at Berlin. Professor of Botany at Jena. Founder (with Schwann) of the cell theory. Ueber Phytogenesis, 1838, English trans. 1847; Grundzüge der wissenschaftlichen Botanik, 1842-1843. *Cf.* Russell, and Sachs.

SCHULTZE, MAX (1825-1874). German biologist. Professor of anatomy at Halle and later succeeded Helmholtz at Bonn. Contributed largely to the conception of protoplasm as the physical basis of all life. Das Protoplasma der Rhizopoden und der Pflanzenzellen, 1863. *Cf.* Locy.

SCHWANN, THEODOR (1810-1882). German zoologist. Pupil of Müller at Bonn. Professor of anatomy, and later physiology at Liège. Founded (with Schleiden) the cell theory. Mikroscopische Untersuchungen, etc., 1839, English trans., 1847. *Cf.* Sachs, and Russell.

SCROPE, GEORGE POULETT (1797-1875). British geologist. Studied at Cambridge. Assumed the name of Scrope after marriage with heiress of Scrope family. Considerations on volcanoes leading to the establishment of a new theory of the Earth, 1825. Geology and extinct volcanoes of central France, 2d ed., 1858. *Cf.* Judd.

SEVERINUS, MARCUS AURELIUS (1580-1656). Italian anatomist. His Zootomia Democritæ, 1645, is an early attempt to make anatomy comparative.

SILLIMAN, BENJAMIN (1779-1864). American chemist and geologist. Graduated from Yale in 1796. Professor of chemistry and mineralogy at Yale, 1802-1853. Probably the most influential representative of science in America during the first half of nineteenth century. Founder, and from 1818 to 1838 the sole editor of, the American Journal of Science and Arts. *Cf.* A Century of Science in America, E. S. Dana, editor; Leading American Men of Science, D. S. Jordan, editor.

SMITH, WILLIAM (1769-1838). Civil engineer and geologist. Called the "Father of English Geology." First recipient of the Wollaston medal. *Cf.* J. Phillips, Memoirs of William Smith, 1844.

SORBY, HENRY CLIFTON (1826-1908). English geologist. One of the founders of petrography in England. In 1882 he became President of

Firth College, Sheffield. Memoir on the microscopical structure of crystals, Quart. Journ. Geol. Soc., 1858. *Cf.* Zittel.

SPALLANZANI, LAZZARO (1729-1799). Italian savant. Successively, professor of logic, mathematics, and Greek at Reggio; professor of natural history at Modena, and at Pavia. Noteworthy contributions to problems of reproduction, circulation, respiration, digestion, etc. Dissertazioni di fisica animale e vegetabile, 1783; Tracts on the nature of animals and vegetables, English translation, 1799; Opere, 1826. *Cf.* Foster; Pavesi's L'Abbato Spallanzani, 1901; and B. Cummings, Spallanzani, Science Progress, 1916.

STEINER, JACOB (1796-1863). Swiss mathematician. Student at Heidelberg and Berlin. Professor of geometry at Berlin. Laid the foundations of synthetic geometry. *Cf.* Gesammelte Werke, 1881.

STENSEN, NIELS (1638-1686). Physiologist, anatomist, geologist, and theologian. Professor of anatomy at Copenhagen; later Apostolic Vicar of Lower Saxony at Florence. Observationes Anatomicæ, 1662. De solido intra solidum naturaliter contento, 1669. *Cf.* Garrison.

STEVINUS, SIMON (1548-1620). Dutch mathematician. Self-educated. Did important original work in the theory of numbers, optics, astronomy, geography. *Cf.* Steichen's Vie et travaux de Simon Stevinus, 1846.

STOKES, GEORGE GABRIEL, SIR (1819-1903). British physicist. Professor of mathematics at Cambridge. Important work in pure mathematics, theory of fluids, sound, and especially in optics. *Cf.* A. Macfarlane's Ten British Physicists, 1919.

STRUVE, WILHELM (1793-1864). Russian astronomer. First director of the Pulkowa Observatory in Russia; made the first systematic study of double stars.

SWAMMERDAM, JAN (1637-1680). Studied medicine at Leyden. A life full of vicissitudes which was brought to an end apparently by over-zealous application to dissections. Biblia Naturæ, edited by H. Boerhaave, 1737-1738, English trans., edited by John Hill, 1758. *Cf.* Boerhaave's biography of Swammerdam in Biblia Naturæ; also Locy, and Miall.

SYLVIUS, FRANCISCUS (1614-1672). Graduated at Basel. Professor of Medicine at Leyden. Instituted first university chemical laboratory. Disputationes, 1663. *Cf.* Foster.

SYLVIUS, JACOBUS (1478-1555). French anatomist. Professor of

medicine at Paris who attracted students from all over Europe, among them Vesalius. *Cf.* Foster, and Garrison.

Tartaglia, Niccolo (1506-1559). Italian mathematician. Professor at Brescia. Discovered the solution of a cubic. Claimed to have invented the gunner's quadrant. Published the first Italian translation of Euclid, 1543. *Cf.* Buoncompagni, Intorno ad un testamento inedito di N. Tartaglia, 1881.

Taylor, Brook (1685-1731). English mathematician. Studied at St. John's, Cambridge, also under J. Machin and J. Keill. Was contemporary of Johann Bernoulli. His Methodus incrementorum directa et inversa added a new branch to mathematics, now called finite differences.

Theophrastus of Eresus (370-286 B. C.). Greek botanist. Pupil and friend of Aristotle, who bequeathed to him his library, manuscripts, and botanic garden. Credited with 227 treatises. Enquiry into Plants, and minor works on odours and weather signs, Greek text with an English translation by Arthur Hort, 1916. *Cf.* Greene.

Thomsen, Hans Peter Jorgen Julius (1826-1909). Danish chemist. Known for his investigations of the heat changes associated with chemical changes.

Thomson, Joseph John, Sir (1856—). British physicist. Educated at Cambridge, became fellow in Trinity College. Succeeded Stokes as Cavendish professor in 1884. Made contributions to mechanics, but his chief work was in the development of the electron theory.

Tournefort, Joseph Pitton de (1656-1708). French botanist. Professor at the Jardin des Plantes. Chief work was in botanical taxonomy. Institutiones Rei Herbariæ, 1700. *Cf.* Greene, and Sachs.

Treviranus, Gottfried Reinhold (1776-1837). German naturalist and student of evolution. Both he and Lamarck coined the term 'biology' the same year. Biologie, oder Philosophie der lebenden Natur, 1802. *Cf.* Osborn.

Turner, William (1510-1568). British zoologist and botanist. A new herball, 1551; Avium præcipuarum, . . . historia, 1544. *Cf.* Miall, and A. Arber, Herbals.

Tycho Brahé (1546-1601). Danish astronomer. Made the most accurate observations up to his time; laid the foundation for Kepler's

work. Astronomical Instauratæ Progymnasmata, 1602-1630. *Cf.* Tycho Brahé by J. L. E. Dreyer, 1890.

Tyson, Edward (1650-1708). London physician. Graduate of, and lecturer at Cambridge. Orang-Outang, sive Homo sylvestris; or The Anatomy of a Pygmie compared with that of a Monkey, an Ape, and a Man, 1699. *Cf.* Russell.

Vesalius, Andreas (1514-1564). Native of Brussels, studied at Louvain, Leyden, and Paris. Surgeon with the imperial troops in Flanders from 1535 to 1537. Professor of surgery in the University of Padua, Court Physician to Charles V and Philip II. Returned with the latter to Spain at the height of the Inquisition. Made a pilgrimage to Jerusalem in 1563 and died on the voyage home. De Humani Corporis Fabrica, 1543. *Cf.* Foster, Stirling, and H. D. White's History of the Warfare of Science with Theology in Christendom, 1900.

Vicq d'Azyr, Felix (1748-1794). French anatomist. Celebrated physician of Paris. Permanent secretary of the Academy of Medicine. *Cf.* Huxley, in Life of R. Owen, 1894.

Vieta, François (1540-1603). French mathematician. Royal privy councillor, and man of wealth. Wrote on trigonometry; first to apply algebraic transformations to this science; solved equations by reductions; denoted general quantities in algebra by letters of the alphabet. Logistica speciosa, Opera Mathematica, 1646.

Vinci, Leonardo da (1452-1519). Italian painter, architect, sculptor, engineer, and anatomist. One of the earliest observers whose opinions have been recorded concerning the history of the earth. Quaderni d'anatomica, with English translation, 1911. *Cf.* Geikie, Garrison, and Zittel.

Vogt, Karl Christoph (1817-1895). German naturalist and geologist. Professor of geology and zoology at Geneva. Grundriss der Geologie, 1860; Lehrbuch der Geologie und Petrefactenkunde, 1846-1847; English version of his Lectures on Man: his Place in Creation and in the History of the Earth, was published by the Anthropological Society of London, 1864.

Volta, Alessandro (1745-1827). Italian physicist. Professor of physics at Como, and at Pavia. Important experimental work in electricity.

WAAGE, PETER (1833-1900). Norwegian chemist. Discovered, with Guldberg, the law of mass-action.

WALLACE, ALFRED RUSSEL (1822-1913). British naturalist, traveler, collector, and evolutionist. Geographical Distribution of Animals, 1876; Letters and Reminiscences, 1916, containing the historic correspondence between Darwin and Wallace on the origin and growth of natural selection. *Cf.* Judd.

WEBER, ERNST HEINRICH (1795-1878). Professor at Leipzig. Wellenlehre (with his brother), 1825; Der Tastsinn und das Gemeingefühl, 1846. *Cf.* Stirling.

WEIERSTRASS, KARL (1815-1897). German mathematician. Professor at Münster, Deutsch-Krone, Braunsberg, and Berlin. Great work was on Abelian functions and transcendents; made the extraordinary discovery of a function which is continuous over an interval and does not possess a derivative at any point on this interval.

WEISMANN, AUGUST (1834-1914). German zoologist. Graduated at Göttingen; professor of zoology at Freiburg. Exponent of evolution. Emphasized the non-inheritance of acquired characters. The Germ Plasm, English trans., 1892. *Cf.* E. G. Conklin, Science, 1915.

WERNER, ABRAHAM GOTTLOB (1750-1817). German geologist. Studied at Freiburg and Leipzig; professor at Freiburg. Von den ausserlichen Kennzeichen der Fossilien, 1774; Kurze Klassifikation und Beschreibung der verschiedenen Gebirgsarten, 1787. *Cf.* Robert Jameson, Elements of Geognosy, 1808; G. Cuvier, Éloge de Werner.

WILLIAMSON, ALEXANDER WILLIAM (1824-1904). English chemist. Did important work on the formation of ethers and on the theory of types in organic compounds.

WÖHLER, FRIEDRICH (1800-1882). German chemist. Discovered new elements and contributed largely to the elucidation of fundamental problems in organic chemistry. Ueber künstliche Bildung des Harnstoffs, 1828.

WOLFF, CASPAR FRIEDRICH (1733-1794). German embryologist. Student at Berlin and Halle. Lectured at Breslau and St. Petersburg. Theoria generationis, 1759; De formatione intestinorum, 1768-1769. *Cf.* Sachs, and Russell.

WOLLASTON, WILLIAM HYDE (1766-1828). English chemist and natural philosopher.

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Wroblewski, Zygmunt Florenty (1845-1888). Polish physicist. Made important contributions to the liquefaction of gases.

Young, Thomas (1773-1829). British physicist. Studied medicine at London, Edinburgh, and Göttingen, and practiced in London. Professor of physics at the Royal Institution. His principal work was in the undulatory theory of light. *Cf.* G. Peacock's Life of Thomas Young, 1855.

Zirkel, Ferdinand (1838-1912). Professor of geology in the University of Lemberg, 1863; at Kiel, 1868; professor of mineralogy and geology at Leipzig. A pioneer in the microscopical investigation of rocks. Lehrbuch der Petrographie, 1866, 2d ed. 1893; Untersuchung über die mikroskopische Zusammensetzung und Struktur der Basaltgesteine, 1870; Die mikroskopische Beschaffenheit der Mineralien und Felsarten, 1873. *Cf.* Zittel.

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APPENDIX III

THE CHEMICAL ELEMENTS ARRANGED IN CHRONOLOGICAL ORDER OF THEIR DISCOVERY, WITH REMARKS AS TO DISCOVERER AND ORIGINAL SOURCE AND DERIVATION OF NAME OR SYMBOL

Name	*Symbol*	*Date*	*Discoverer*	*Original source and derivation of name or symbol*
1. gold	Au		known to the ancients, though not as elements in the modern sense	Found native; Latin "aurum"
2. silver	Ag			Found native; Latin "argentum"
3. copper	Cu			Found native; Latin "cuprum," from Cyprus
4. iron	Fe			Found native; Latin "ferrum"
5. mercury	Hg			Found native; Latin "hydrargyrum" (= quick silver)
6. sulphur	S			Found native; Latin "sulphur"
7. lead	Pb			Found native; Latin "plumbum"
8. tin	Sn			Found native; Latin "stannum"
9. carbon	C			Charcoal; Latin "carbo" (= coal)
10. arsenic	As	1250(?)	Albertus Magnus	Greek ἀρσενικόν (= masculine)
11. antimony	Sb	1490(?)	Basil Valentine	Latin "stibium," properly the ore, antimony sulphide
12. bismuth	Bi	1530(?)	Agricola	Unknown
13. zinc	Zn	1600(?)	Paracelsus	Unknown
14. phosphorus	P	1669	Brand	Greek φοσφόρος (= lightbearer)
15. cobalt	Co	1735	G. Brandt	German "Kobold," a goblin or demon, because it was troublesome to miners

Continued

Name	*Symbol*	*Date*	*Discoverer*	*Original source and derivation of name or symbol*
16. platinum	Pt	1750	W. Watson, from Wood, assay-master Jamaica	Found native; initially "platina," so called from its resemblance to silver (Spanish "plata")
17. nickel	Ni	1751	A. F. Cronstedt	From Kupfernickel; German "nickel," the devil; *cf.* cobalt
18. nitrogen	N	1772	D. Rutherford	From air; the "niter-producer"; originally called azote, from its inability to support respiration
19. chlorine	Cl	1774	Scheele	From salt; in allusion to its greenish color; established as an element about 1810 by Davy
20. oxygen	O	1774	Priestley	From air; the "acid-producer," because supposed to be a constituent of all acids
21. manganese	Mn	1774	J. G. Gahn	From its oxide, originally "magnesia nigra," subsequently "manganesia" to distinguish from "magnesia (alba)"
22. tungsten	W	1783	d'Elhujar	Swedish "heavy stone"; symbol from Wolframite, a mineral containing tungsten
23. molybdenum	Mo	1783	P. T. Hjelm	From Greek μόλυβδος (lead), with compounds of which its compounds were frequently confused
24. hydrogen	H	1784	Cavendish	From water; the "water-producer"
25. uranium	U	1789	Klaproth	After the planet Uranus
26. titanium	Ti	1791	Gregor	In allusion to the Titans
27. chromium	Cr	1797	Vauquelin	In allusion to the fine color of its salts

Continued

Name	*Symbol*	*Date*	*Discoverer*	*Original source and derivation of name or symbol*
28. tellurium	Te	1798	Klaproth	After "Tellus," the earth
29. columbium	Cb	1802	Hatchett	From Columbite, after Columbia, being discovered in America; also called niobium, after Niobe, a daughter of Tantalus, because obtained from an impure tantalum.
30. tantalum	Ta	1802	Ekeberg	After Tantalus, because its behavior seemed tantalizing
31. palladium	Pd	1803	Wollaston	After the planet Pallas, then newly discovered
32. rhodium	Rh	1803	Wollaston	In allusion to rose color (Greek ῥόδεος) of its salts
33. iridium	Ir	1803	DeCotils & Smithson-Tennant	From "iris," in allusion to the changing tints of its oxides
34. osmium	Os	1803	Smithson-Tennant	In allusion to the odor (Greek ὀσμή) of its oxide
35. cerium	Ce	1803	Klaproth; Hisinger & Berzelius	After the planet Ceres
36. potassium	K	1807	Davy	From pot-ash; symbol from Kalium (al-Kali)
37. sodium	Na	1807	Davy	From soda; symbol from Arabic "natron"
38. barium	Ba	1807	Davy	From barytes (Greek βάρος = weight)
39. strontium	Sr	1807	Davy	From strontianite, found at Strontian in Argyllshire
40. calcium	Ca	1807	Davy	From lime; Latin "calx"
41. boron	B	1807	Davy	From borax
42. iodine	I	1811	Courtois	In allusion to violet color (Greek ἰώδης) of vapor
43. cadmium	Cd	1817	Stromeyer	From "cadmia," a zinc mineral

Continued

Name	Symbol	Date	Discoverer	Original source and derivation of name or symbol
44. lithium	Li	1818	Arfvedson	Greek λίθος, a stone
45. selenium	Se	1818	Berzelius	Greek σελήνη, the moon
46. zirconium	Zr	1824	Berzelius	From the mineral zircon, from which in 1788 Klaproth had isolated the oxide zirconia
47. silicon	Si	1824	Berzelius	From silica; Latin "silex," flint
48. bromine	Br	1826	Balard	In allusion to its smell (Greek βρῶμος, a stink)
49. aluminium	Al	1828	Wöhler	From alum
50. glucinum	Be	1828	Wöhler	From beryl; name in allusion to the sweet taste of some of its salts; also called beryllium
51. ruthenium	Ru	1828	Osann	After Ruthenia (Russia)
52. thorium	Th	1828	Berzelius	After Thor, the Nordic god
53. magnesium	Mg	1829	Bussy	From magnesia; *cf.* manganese
54. vanadium	V	1830	Sefström	After Vanadis, the Scandinavian goddess Freya
55. lanthanum	La	1839	Mosander	Separated from ceria; from Greek λανθάνειν, to lie hidden
56. caesium	Cs	1860	Bunsen & Kirchhoff	In allusion to the characteristic blue lines (Latin "cæsius," sky-blue) in its spectrum
57. rubidium	Rb	1861	Bunsen & Kirchhoff	In allusion to the characteristic red line (Latin "rubidus") in its spectrum
58. thallium	Tl	1861	Crookes	In allusion to its green spectrum line (Greek θαλλός, a green shoot)
59. indium	In	1863	Reich & Richter	In allusion to its blue spectrum line (Latin "indicum," indigo)

Continued

Name	*Symbol*	*Date*	*Discoverer*	*Original source and derivation of name or symbol*
60. gallium	Ga	1875	Boisbaudran	After Gallia (France)
61. scandium	Sc	1879	Nilson	After Scandia (Scandinavia)
62. germanium	Ge	1886	Winkler	After Germania (Germany)
63. fluorine	F	1886	Moissan	From fluorspar, so called because used as a flux
64. yttrium	Y	1843	Mosander	First detected in gadolinite, found at Ytterby in Sweden; whence the names
65. erbium	Er	1843 1860 1879	Mosander Berlin Cleve	
66. terbium	Tb	1878 1886	Soret Marignac	
67. thulium	Tm	1879	Cleve	From Mosander's erbia; after "Thule" (Scandinavia)
68. holmium	Ho	1879 1886	Cleve Boisbaudran	From Soret's X; named after Stockholm
69. gadolinium	Gd	1880 1886	Marignac Boisbaudran	From samarskite; after the mineralogist Gadolin
70. praseodymium	Pr	1885	von Welsbach	By separation of Mosander's didymia, Greek *δίδυμοι* twins; *πρασαῖος* leek green, in allusion to color of its salts
71. neodymium	Nd	1885	von Welsbach	
72. dysprosium	Dy	1886	Boisbaudran	From Cleve's holmia; from Greek *δυσπρόσιτος*, in allusion to the difficulty of isolating it

Concluded

Name	*Symbol*	*Date*	*Discoverer*	*Original source and derivation of name or symbol*
73. samarium	Sa	1900	Demarçay	From Boisbaudran's samaria (1879), derived from Mosander's didymia; names from samarskite, and in allusion to Europe
74. europium	Eu	1901	Demarçay	
75. ytterbium	Yb	1907	Urbain	From Marignac's ytterbia (1878); Latin "Lutetia," Paris
76. lutecium	Lu	1907	Urbain	
77. argon	A	1894	Rayleigh & Ramsay	From air; name in allusion to its inertness
78. helium	He	1895	Ramsay	From cleveite; characteristic line noticed thirty years earlier in spectrum of sun (Greek ἥλιος)
79. krypton	Kr	1895	Ramsay & Travers	From air; "The hidden one"
80. neon	Ne	1895	Ramsay & Travers	From air; "The new one"
81. xenon	Xe	1895	Ramsay & Travers	From air; "The stranger"
82. radium	Ra	1903	Madame S. Curie	From pitchblende, a uranium mineral; Latin "radius," a ray
83. polonium	Po	1903	Madame S. Curie	From uranium residues; Latin "Polonia," Poland
84. actinium	Ac	1904	Debierne	From pitchblende; in allusion to its radioactivity
85. radio-thorium		1905	Hahn	From thorium
86. meso-thorium		1905	Hahn	From thorium
87. ionium		1906	Boltwood	From uranium residues; from "ion," a wanderer
88. radium emanation		1910	Ramsay & Soddy	Sometimes called niton, "the shining one"

TERMS OF THE GEOLOGIC COLUMN; THEIR ORIGIN AND SIGNIFICANCE

By Walter B. Lang.

Psychozoic	1877	Joseph Le Conte. In the words of Le Conte, the "reign of mind." Gr. ψυχή mind, ζωή life.
Quaternary	1829	Jules Desnoyers. The fourth division. Latin quaternarius, of four each.
Pleistocene	1839	Charles Lyell. Most recent. Gr. πλεῖστος most, καινός recent.
Pliocene	1833	Charles Lyell. More recent. Gr. πλείων more, καινός recent.
Miocene	1833	Charles Lyell. Less recent. Gr. μείων less, καινός recent.
Oligocene	1854	Heinrich Ernst Beyrich. Little of recent. Gr. ὀλίγος few, little, καινός recent.
Eocene	1833	Charles Lyell. Dawn of recent. Gr. ἠώς dawn, καινός recent.
Paleocene	1874	Philipp Wilhelm Schimper. Ancient recent. Gr. παλαιός ancient, καινός recent.
Tertiary	1808	Georges Cuvier and Alexandre Brongniart. The third division. Latin tertiarius from tertius, the third.
Cretaceous	1822	Jean d'Omalius d'Halloy. From the Latin creta, chalk.
Comanchean	1887	Robert Thomas Hill. From the town of Comanche, Texas—originally an Indian name.
Jurassic	1829	Alexandre Brongniart. From the Jura Mountains of northwest Switzerland.
Triassic	1834	Friedrich August von Alberti. From the three divisions, Bunter, Muschelkalk, Keuper—Germany.
Permian	1841	Roderick Impey Murchison. From the government of Perm, Russia.

Terms of the Geologic Column; Their Origin and Significance—(Continued)

Pennsylvanian	1891	Henry Shaler Williams. From the state of Pennsylvania.
Mississippian	1869	Alexander Winchell. From the Mississippi River basin.
Carboniferous	1822	William Daniel Conybeare and John Phillips. From the abundance of coal formations contained within the system.
Devonian	1839	Roderick Impey Murchison and Adam Sedgwick. From Devonshire in southern England.
Silurian	1835	Roderick Impey Murchison. From the tribe of ancient Britons in western England and Wales, the Silures.
Ordovician	1879	Charles Lapworth. From the ancient tribe of Ordovices, Wales.
Ozarkian	1911	Edward Oscar Ulrich. From the Ozark Mountains of Missouri.
Croixan	1873	Newton Horace Winchell. From the St. Croix valley, Minnesota-Wisconsin.
Acadian	1868	John William Dawson. From the maritime provinces of eastern Canada.
Waucoban	1912	Charles Doolittle Walcott. From Waucoba Springs, Inyo County, California.
Cambrian	1835	Adam Sedgwick. From the Roman name for northern Wales.
Cenozoic	1840	John Phillips. Recent life. Gr. καινός recent, ζωή life.
Mesozoic	1840	John Phillips. Middle life. Gr. μέσος middle, ζωή life.
Paleozoic	1838	Adam Sedgwick. Ancient life. Gr. παλαιός ancient, ζωή life.
Lipalian	1910	Charles Doolittle Walcott. The lost interval. Gr. λείπα missing, ἅλς sea.

Terms of the Geologic Column; Their Origin and Significance—(Concluded)

Keweenawan	1876	T. B. Brooks. From Keeweenaw Peninsula, Michigan.
Animikian	1873	Thomas Sterry Hunt. An Indian name for Thunder Bay on the northwest shore of Lake Superior.
Sudburian	1913	Arthur Philemon Coleman. From Sudbury, Ontario.
Algoman	1913	Andrew Cowper Lawson. An Indian name from Ontario, Canada.
Huronian	1855	William Edmond Logan and T. Sterry Hunt. From Lake Huron.
Algonkian	1889	Charles Doolittle Walcott. An Indian name from the Great Lakes region.
Laurentian	1854	William Edmond Logan. From the Laurentide Mountains of Quebec, Canada.
Grenville	1863	William Edmond Logan. From Grenville, Quebec, on the Ottawa River.
Keewatin	1885	Andrew Cowper Lawson. An Indian name from the province of Keewatin, Canada.
Coutchiching	1887	Andrew Cowper Lawson. An Indian name from the Rainy Lake region of Minnesota and Ontario.
Archean	1872	James Dwight Dana. Ancient origin. Gr. ἀρχαῖος ancient, ἀρχή beginning.
Azoic	1845	Murchison, Verneuil and Keyserling. Without life. Gr. ἀ without, ζωή life.

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